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Cohomology of Arithmetic Groups

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Preface

Finally this is now the book on "Cohomology of Arithmetic Groups" which was announced in my "Lectures on Algebraic Geometry I and II." It starts with Chapter II because the material in what would be Chapter I is covered in the first four chapters of LAG I. In these four chapters we provide the basics of homological algebra which are needed in this volume.

During the years 1980-2000 I gave various advanced courses on number theory, algebraic geometry and also on "cohomology of arithmetic groups" at the university of Bonn. I prepared some notes for the lectures on "cohomology of arithmetic groups", because there was essentially no literature covering this subject.

At some point I had the idea to use these notes as a basis for a book on this subject, a book that introduced into the subject but that also covered applications to number theory.

It was clear that a self-contained exposition needs some preparation, we need homological algebra and later if we treat Shimura varieties, we need also a lot of algebraic geometry, especially the concept of moduli spaces. Since the cohomology groups of arithmetic groups are sheaf cohomology groups, and since the theory of sheaves and sheaf cohomology is ubiquitous in algebraic geometry I had the idea to write a volume "Lectures on Algebraic Geometry" where I discuss the impact of sheaf theory to algebraic geometry. This volume became the two volumes mentioned above and the writing of these volume is at last partly responsible for the delay.

The applications to number theory concern the relationship between special values of L-functions and the integral structure of the cohomology as module under the Hecke algebra. On the one hand we can prove rationality statements for special values (Manin and Shimura) on the other these special values tell us something about the denominators of the Eisenstein classes. These connections was already discussed in the original notes in 1985 for the special case of $\mathrm{Sl}_2(\mathbb{Z})$. and the precise results are stated at the end of Chapter II.

In more general cases this relationship is conjectural and it was very important for me that these conjectures got some support by experimental calculations by G. van der Geer and C. Faber and others.

This tells us that the whole subject has interesting aspects from the computational side. In Chapter II we discuss a strategy to compute the cohomology and the Hecke endomorphisms explicitly so that we can verify the above conjectures in explicit examples. For the group $\mathrm{Sl}_2(|Z)$ such explicit calculations have been done by my former student X.-D. Wang in his Bonn dissertation and are now resumed in Chapter II.

I hope that this book will be a substantial contribution to a beautiful field in mathematics, it contains interesting results and it also points to challenging questions.

Contents

0.1 Introduction

This book is meant to be an introduction into the cohomology of arithmetic groups. This is certainly a subject of interest in its own right, but my main goal will be to illustrate the arithmetical applications of this theory. I will discuss the application to the theory of special values of L-functions and the theorem of Herbrand-Ribet (See Chap V, [Ri], Chap VI, Theorem II).

Our main objects of interest are the cohomology groups of locally symmetric spaces $\Gamma\backslash X$ with coefficients in sheaves $\tilde{\mathcal{M}}$ which are obtained from a finitely generated Γ-module M, they will be denoted by $H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})$.

On the other hand the subject is also of interest for differential geometers and topologists, since the arithmetic groups provide so many interesting examples of Riemannian manifolds.

My intention is to write an elementary introduction. The text should be readable by graduate students. This is not easy, since the subject requires a considerable background: One has to know some homological algebra (cohomology and homology of groups, spectral sequences, cohomology of sheaves), the theory of Lie groups, the structure theory of semisimple algebraic groups, symmetric spaces, arithmetic groups, reduction theory for arithmetic groups. At some point the theory of automorphic forms enters the stage, we have to understand the theory of representations of semi-simple Lie groups and their cohomology. Finally when we apply all this to number theory (in Chap. V and VI) one has to know a certain amount of algebraic geometry ($\ell-$adic cohomology, Shimura varieties (in the classical case of elliptic modular functions)) and some number theory(classfield theory, $L-$functions and their special values).I

will try to explain as much as possible of the general background. This should be possible, because already the simplest examples namely the Lie groups $\mathrm{Sl}_2(\mathbb{R})$ and $\mathrm{Sl}_2(\mathbb{C})$ and their arithmetic subgroups $\mathrm{Sl}_2(\mathbb{Z})$ and $\mathrm{Sl}_2(\mathbb{Z}[\sqrt{-1}])$ are very interesting and provide deep applications to number theory. For these special groups the results needed from the structure theory of semisimple groups, the theory of symmetric spaces and reduction theory are easy to explain. I will therefore always try to discuss a lot of things for our special examples and then to refer to the literature for the general case.

I want to some words about the general framework.

Arithmetic groups are subgroups of Lie groups. They are defined by arithmetic data. The classical example is the group $\mathrm{Sl}_2(\mathbb{Z})$ sitting in the real Lie group $\mathrm{Sl}_2(\mathbb{R})$ or the group $\mathrm{Sl}_2(\mathbb{Z}[\sqrt{-1}])$ as a subgroup of $\mathrm{Sl}_2(\mathbb{C})$, which has to be viewed as real Lie group (See ..). Of course we may also consider $\mathrm{Sl}_n(\mathbb{Z}) \subset \mathrm{Sl}_n(\mathbb{R})$ as an arithmetic group. We get a slightly more sophisticated example, if we start from a quadratic form, say

$$f(x_1, x_2, \dots, x_n) = -x_1^2 + x_2^2 + \cdots + x_n^2$$

the orthogonal group $O(f)$ is a linear algebraic group defined over the field $\mathbb{Q}$ of rational numbers, the group of its real points is the group $O(n,1) = O(f)(\mathbb{R})$ and the group of integral matrices preserving this form is an arithmetic subgroup $\Gamma \subset O(f)(\mathbb{R})$

The starting point will be an arithmetic group $\Gamma \subset G_\infty$, where G_∞ is a real Lie group. This group is always the group of real points of an algebraic group over $\mathbb{Q}$ or a subgroup of finite index in it. To this group G_∞ one associates a symmetric space $X = G_\infty/K_\infty$, where K_∞ is a maximal compact subgroup of G_∞, this space is diffeomorphic to $\mathbb{R}^d$. The next datum we give ourselves is a Γ-module $\mathcal{M}$ from which we construct a sheaf $\tilde{\mathcal{M}}$ on the quotient space $\Gamma\backslash X$. This sheaf will be what topologists call a local coefficient system, if Γ acts without fixed points on X. We are interested in the cohomology groups

$$H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}}).$$

Under certain conditions we have an action of a big algebra of operators on these cohomology groups, this is the so called Hecke algebra $\mathcal{H}$, it originates from the structure of the arithmetic group Γ (Γ has many subgroups of finite index, which allow the passage to coverings of $\Gamma\backslash X$ and we have maps going back and forth). It is the structure of the cohomology groups $H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})$ as a module under this algebra H, which we want to study, these modules contain relevant arithmetic information.

Now I give an overview on the Chapters of the book.

In chapter I we discuss some basic concepts from homological algebra, especially we introduce to the homology and cohomology of groups, we recall some facts from the cohomology of sheaves and give a brief introduction into the theory of spectral sequences

.

Chapter II introduces to the theory of linear algebraic groups, to the theory of semi simple algebraic groups and the corresponding Lie groups of their real points. We give some examples and we say something about the associated symmetric spaces. We consider the action of arithmetic groups on these symmetric spaces, and discuss some classical examples in detail. This is the content of reduction theory. As a result of this we introduce the Borel-Serre compactification $\Gamma\backslash\bar{X}$ of $\Gamma\backslash X$, which will be discussed in detail for our examples. After this we take up the considerations of chapter I and define and discuss the cohomology groups of arithmetic groups with coefficients in some Γ-modules $\mathcal{M}$. We shall see that these cohomology groups are related (and under some conditions even equal) to the cohomology groups of the sheaves $\tilde{\mathcal{M}}$ on $\Gamma\backslash X$. Another topic in this chapter is the discussion of the homology groups, their relation to the cohomology with compact supports and the Poincaré duality. We will also explain the relations between the cohomology with compact supports the ordinary cohomology and the cohomology of the boundary of the Borel-Serre compactification. Finally we introduce the Hecke operators on the cohomology. We discuss these operators in detail for our special examples, and we prove some classically well known relations for them in our context. In these classical cases we also compute the cohomology of the boundary as a module over the Hecke algebra $\mathcal{H}$

At the end of this chapter we give some explicit procedures, which allow an explicit computation of these cohomology groups in some special cases. It may be of some interest to develop such computational techniques since this allows to carry out numerical experiments (See .. and ...). We shall also indicate that this apparently very explicit procedure for the computation of the cohomology does not give any insight into the structure of the cohomology as a module under the Hecke algebra. This chapter II is still very elementary.

In Chapter III we develop the analytic tools for the computation of the cohomology. Here we have to assume that the Γ-module $\mathcal{M}$ is a $\mathbb{C}$-vector space and is actually obtained from a rational representation of the underlying algebraic group. In this case one may interprete the sheaf $\tilde{\mathcal{M}}$ as the sheaf of locally constant sections in a flat bundle, and this implies that the cohomology is computable from the de-Rham-complex associated to this flat bundle. We could even go one step further and introduce a Laplace operator so that we get some kind of Hodge-theory and we can express the cohomology in terms of harmonic forms. Here we encounter serious difficulties since the quotient space $\Gamma\backslash X$ is not compact. But we will proceed in a different way. Instead of doing analysis on $\Gamma\backslash X$ we work on $\mathcal{C}_\infty(\Gamma\backslash G_\infty)$. This space is a module under the group G_∞, which acts by right translations, but we rather consider it as a module under the Lie algebra $\mathfrak{g}$ of G_∞ on which also the group K_∞ acts, it is a $(\mathfrak{g}, K)$-module.

Since our module $\mathcal{M}$ comes from a rational representation of the underlying group G, we may replace the de-Rham-complex by another complex

$$H^\bullet(\mathfrak{g}, K_\infty, \mathcal{C}_\infty(\Gamma\backslash G_\infty) \otimes \mathcal{M},$$

this complex computes the so called $(\mathfrak{g}, K)$-cohomology. The general principle will be to "decompose" the $(\mathfrak{g}, K)$-module $\mathcal{C}_\infty$ into irreducible submodules and therefore to compute the cohomology as the sum of the contributions of the individual submodules. This is a group theoretic version of the classical approach by Hodge-theory. Here we have to overcome two difficulties. The first one is that the quotient $\Gamma\backslash G_\infty$ is not compact and hence the above decomposition does not make sense, the second is that we have to understand the irreducible $(\mathfrak{g}, K)$-modules and their cohomology. The first problem is of analytical nature, we will give some indication how this can be solved by passing to certain subspaces of the cohomology the so called cuspidal and the discrete part of the cohomology. We shall state some general results, which are mainly due to A. Borel and H. Garland. We shall shall also state some general results concerning the second problem. The general result in this chapter is a partial generalization of the theorem of Eichler-Shimura, it describes the cuspidal part of the cohomology in terms of irreducible representations occurring in the space of cusp forms and contains some information on the discrete cohomology, which is slightly weaker. We shall also give some indications how it can be proved.

In the next chapter IV we resume the discussion of the previous chapter but we restrict our attention to the specific groups $\mathrm{Sl}_2(\mathbb{R})$ and $\mathrm{Sl}_2(\mathbb{C})$ and their arithmetic subgroups. At first we give a rather detailed discussion of their representation-theory (i.e. the theory of representations of the corresponding $(\mathfrak{g}, K)$-modules) and we compute also the $(\mathfrak{g}, K)$-cohomology of the most important $(\mathfrak{g}, K)$-modules, this is the second ingredient in the theorem of Eichler -Shimura. But in this special case we give also a complete solution for the analytical difficulties, so that in this case we get a very precise formulation of the Eichler-Shimura theorem, together with a rather complete proof.

In the following chapter V we discuss the Eisenstein-cohomology. The theorem of Eichler-Shimura describes only a certain part of the cohomology , the Eisenstein -cohomology is meant to fill the gap, it is complementary to the cuspidal cohomology. These Eisenstein classes are obtained by an infinite summation process, which sometimes does not converge and is made convergent by analytic continuation. We shall discuss in detail the cases of the special groups $\mathrm{Sl}_2(\mathbb{R})$ and $\mathrm{Sl}_2(\mathbb{C})$ (the second case is not yet in the manuscript). Here we will be able to explain an arithmetic application of our theory. Recall that we have to start from a rational representation of the underlying algebraic group $G/\mathbb{Q}$ and this representation is defined over $\mathbb{Q}$ or at least over some number field. Hence we actually get a Γ-module $\mathcal{M}$ which is a $\mathbb{Q}$- vector space, and hence we may study the cohomology $H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})$ which then is a $\mathbb{Q}$-vector space. The Eisenstein classes are a priori defined by transcendental means, so they define a subspace in $H^\bullet(\mathrm{Lie}g, K, \tilde{\mathcal{M}})_\mathbb{C}$. But we have still the action of the Hecke-algebra $\mathbf{H}$, and this acts on the $\mathbb{Q}$-vector space $H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})$, and using the so called Manin-Drinfeld argument we can characterize the space of Eisenstein-classes as an isotypical piece in the cohomology, hence it is defined over $\mathbb{Q}$. We shall indicate that we can evaluate the now rational Eisenstein-classes on certain homology-classes, which are also defined over $\mathbb{Q}$, hence the result is a rational number. On the other hand we can-using the transcendental definition of the Eisenstein class-express the result of this evaluation in terms of special values of $L-$functions. This yields rationality results for special values of $L-$functions (see [Ha] and [Ha -Sch]). This gives us the first arithmetic informations of our theory. In Chapter VI we discuss the arithmetic properties of the Eisenstein-

classes. in the previous chapter we have seen, that the Eisenstein-classes are rational classes despite of the fact, that they are obtained by an infinite summation. Now we will discuss the extremely special case where $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$ and our Γ-module is

$$\mathcal{M}_n = \{\sum a_\nu X^\nu Y^{n-\nu} |\ a_\nu \in \mathbb{Z}[\frac{1}{6}]\}.$$

We also introduce the dual module

$$\mathcal{M}_n^\vee = \mathrm{Hom}(\mathcal{M}, \mathbb{Z}[\frac{1}{6}]).$$

We then ask whether the Eisenstein-class is actually an integral class, this means whether it is contained in $H^1(\Gamma\backslash X), \mathcal{M}_n^\vee)$. The answer is no in general, the Eisenstein-class has a denominator, which is apart from powers of 2 and 3 exactly the numerator of the number

$$\zeta(1-(n+2)) = \pm\frac{B_{n+2}}{n+2}.$$

(See Chap. VI, Theorem I) This result is obtained by testing the Eisenstein-classes on certain homology classes, the so called modular symbols, which have been introduced in chapter II. This result generalizes results of Haberland [Hab] and my student [Wg]. I will indicate that this result has arithmetic implications in the direction of the theorem of Herbrand -Ribet. We cannot prove this theorem here since we need some other techniques from arithmetic algebraic geometry to complete the proof. We shall also discuss some congruence relations between Eisenstein classes of different weights, which arise from congruence relations on the level of sheaves. These congruence relations between the sheaves have also been exploited by Hida and R. Taylor

Finally I want to discuss some possible generalizations of all this and some open interesting problems. During the whole book I always tried to keep the door open for such generalizations. I presented the cohomology of arithmetic groups in such a way that we have the necessary tools to extend our results. This may have had the effect, that the presentation of the results in the classical case of $\mathrm{Sl}_2(\mathbb{Z})$ looks to complicated, but I hope it will pay later on.

Some of these generalisations are discussed in [HS].

Chapter 1

Basic Notions and Definitions

1.1 Affine algebraic groups over $\mathbb{Q}$.

A linear algebraic group $G/\mathbb{Q}$ is a subgroup $G \subset GL_n$, which is defined as the set of common zeroes of a set of polynomials in the matrix coefficients where in addition these polynomials have coefficients in $\mathbb{Q}$. Of course we cannot take just any set of polynomials the set has to be somewhat special before its common zeroes form a group. The following examples will clarify what I mean:

1.) The group GL_n is an algebraic group itself, the set of equations is empty. It has the subgroup $\mathrm{Sl}_n \subset GL_n$, which is defined by the polynomial equation

$$\mathrm{Sl}_n = \{x \in GL_n \mid \det(x) = 1\}$$

2.) Another example is given by the orthogonal group of a quadratic form

$$f(x_1, \dots, x_n) = \sum_{i=}^{n} a_i x_i^2$$

where $a_i \in \mathbb{Q}$ and all $a_i \neq 0$ (this is actually not necessary for the following). We look at all matrices

$$\alpha = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \vdots & & \vdots \\ a_{n1} & \dots & a_{nn} \end{pmatrix}$$

which leave this form invariant, i.e.

$$f(\alpha \underline{x}) = f(\underline{x})$$

for all vectors $\underline{x} = (x_1, \dots, x_n)$. This defines a set of polynomial equations for the coefficient a_{ij} of α.

3.) Instead of taking a quadratic form — which is the same as taking a symmetric bilinear form — we could take an alternating bilinear form

$$\begin{aligned}\langle \underline{x}, \underline{y} \rangle =& \langle x_1, \dots, x_{2n}, y_1, \dots y_{2n} \rangle = \\ & \sum_{i=1}^{n} \langle x_1 y_{i+n} - x_{i+n} y_i \rangle = f \langle \underline{x}, \underline{y} \rangle .\end{aligned}$$

This form defines the symplectic group:

$$Sp_n = \left\{ \alpha \in GL_{2n} \mid \langle \alpha \underline{x}, \alpha \underline{y} \rangle = \langle \underline{x}, \underline{y} \rangle \right\}.$$

1.1. Important remark: The reader may have observed that I did not specify a field (or a ring) from which I take the entries of the matrices. This is done intentionally, because we may take the entries from any ring R containing the rational numbers $\mathbb{Q}$. In other words: for any algebraic group $G/\mathbb{Q} \subset GL_n$ and any ring R containing $\mathbb{Q}$ we may define

$$G(R) \subset GL_n(R)$$

as the group of those matrices whose coefficients satisfy the required polynomial equations.

Adopting this point of view we can say that

A linear algebraic group $G/\mathbb{Q}$ defines a functor from the category of $\mathbb{Q}$-algebras (i.e. commutative rings containing $\mathbb{Q}$) into the category of groups.

4.) Another example is obtained by the so-called restriction of scalars. Let us assume we have a finite extension $K/\mathbb{Q}$, we consider the vector space $V = K^n$. This vector space may also be considered as a $\mathbb{Q}$-vector space V_0 of dimension $n[K : \mathbb{Q}] = N$. We consider the group

$$GL_N/\mathbb{Q}.$$

Our original structure as a K-vector space may be considered as a map

$$\Theta : K \longrightarrow \operatorname{End}_{\mathbb{Q}}(V_0),$$

and the group $GL_n(K)$ is then the subgroup of elements in $GL_N(\mathbb{Q})$ which commute with all the elements of $\Theta(x), x \in K$. Hence we define the subgroup

$$G/\mathbb{Q} = R_{K/\mathbb{Q}}(GL_n) = \{\alpha \in GL_N \mid \alpha \text{ commutes with } \Theta(K)\}$$

and $G(\mathbb{Q}) = GL_n(K)$. For any $\mathbb{Q}$-algebra R we get

$$G(R) = GL_n(K \otimes_{\mathbb{Q}} R).$$

This can also be applied to an algebraic subgroup $H/K \hookrightarrow GL_n/K$, i.e. a subgroup that is defined by polynomial equations with coefficients in K.

Our definition of a linear algebraic group is a little bit provisorial. If we consider for instance the two linear algebraic groups

$$\begin{aligned} G_1/\mathbb{Q} &= \left\{ \begin{pmatrix} 1 & x \\ 0 & 1 \end{pmatrix} \right\} \subset \mathrm{Gl}_2 \\ G_2/\mathbb{Q} &= \left\{ \begin{pmatrix} 1 & 0 & x \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right\} \subset GL_3 \end{aligned}$$

then we would like to say, that these two groups are isomorphic. They are two different "realizations" of the additive group $G_a/\mathbb{Q}$. We see that the same linear algebraic group may be realized in different ways as a subgroup of different GL_N's.

Of course there is a concept of linear algebraic group which does not rely on embeddings. The understanding of this concept requires a little bit of affine algebraic geometry. The drawback of our definiton here is that we cannot define morphism between linear algebraic group. Especially we do not know when they are isomorphic. I assert the reader that the general theory implies that a morphism between two algebraic groups is the same thing as a morphism between the two functors form $\mathbb{Q}$-algebras to groups. In some sense it is enough to give this functor. For instance, we have the multiplicative group $\mathbb{G}_m/\mathbb{Q}$ given by the functor

$$R \longrightarrow R^\times$$

and the additive group $G_a/\mathbb{Q}$ given by $R \to R^+$.

We can realize (represent is the right term) the the group $\mathbb{G}_m/\mathbb{Q}$ as

$$\mathbb{G}_m/\mathbb{Q} = \left\{ \begin{pmatrix} t & 0 \\ 0 & t^{-1} \end{pmatrix} \right\} \subset \mathrm{Gl}_2$$

1.1.1 Affine groups schemes

We say just a few words concerning the systematic development of the theory of linear algebraic groups.

For any field k an affine k-algebra is a finitely generated algebra A/k, i.e. it is a commutative ring with identity, containing k, the identity of k is equal to the identity of A, which is finitely generated over k as an algebra. In other words

$$A = k[x_1, x_2, \ldots, x_n] = k[X_1, X_2, \ldots, X_n]/I,$$

where they X_i are independent and where I is a finitely generated ideal of polynomials in $k[X_1, \ldots, X_n]$.

Such an affine k-algebra defines a functor from the category of k algebras to the category of sets

$$B \mapsto \mathrm{Hom}_k(A, B).$$

A structure of a group scheme on A/k consists of the following data:

a) A k homomorphism $m : A \to A \otimes_k A$ (the comultiplication)

b) A k-valued point $e : A \to k$ (the identity element)

c) An inverse $inv : A \to A$,

which satisfy certain requirements:

We have $\mathrm{Hom}_k(A \otimes_k A, B) = \mathrm{Hom}_k(A, B) \times \mathrm{Hom}_k(A, B)$ and hence m defines a map ${}^t m : \mathrm{Hom}_k(A, B) \times \mathrm{Hom}_k(A, B) \to \mathrm{Hom}_k(A, B)$.

The requirement is that for all B this composition map ${}^t m$ defines a group structure on $\mathrm{Hom}_k(A, B)$. The k valued point e is the identity and inv yields the inverse.

I leave it to the audience to figure out what this means for m, e, inv. An affine k together with such a collection m, e, inv is called an affine group scheme.

Now it is clear what a homomorphism between affine group schemes is.

It is a not entirely obvious theorem that for any affine group scheme $G/k = (A/k, m, e, inv)$ we can find a faithful representation $i : G/k \hookrightarrow \mathrm{Gl}(V)$.

We may also consider linear algebraic group over other fields K. This means that we only require the coefficients of the defining polynomials to be in this other field. We write G/K for a group defined over K. Then we have the permission to consider the groups $G(R)$ for any ring containing K.

If we have a field $L \supset K$ and a linear group G/K then the group $G/L = G \times_K L$ is the group over L where we forget that the coefficients of the equations are contained in K. The group $G \times_K L$ is the *base extension* from G/K to L

Tori, their character module,...

A special class of algebraic groups is given by the *tori.* An algebraic group T/K over a field K is called a *split torus* if it is isomorphic to a product of $\mathbb{G}_m$-s. It is called a torus if it becomes a split torus after a suitable finite extension of the ground field, i.e we have $T \times_K L \xrightarrow{\sim} \mathbb{G}_m^r/L$.

If we take an arbitrary finite field extension $L/\mathbb{Q}$ we may consider the functor

$$R \to (L \otimes_{\mathbb{Q}} R)^\times.$$

It is not hard to see that this functor can be represented by an algebraic group over $\mathbb{Q}$, which is denoted by $R_{L/\mathbb{Q}}(\mathbb{G}_m/L)$ and called the Weil restriction of $\mathbb{G}_m/L$. We propose the notation

$$R_{L/\mathbb{Q}}(\mathbb{G}_m/L) = \mathbb{G}_m^{L/Q} \tag{1.1}$$

The reader should try to prove that for a finite extension $\tilde{L}/L$ which is normal over $\mathbb{Q}$ we have

$$\mathbb{G}_m^{L/Q} \times_{\mathbb{Q}} \tilde{L} \xrightarrow{\sim} (\mathbb{G}_m/\tilde{L})^{[L:\mathbb{Q}]}$$

and this shows that $\mathbb{G}_m^{L/Q}$ is a torus .

A torus T/K is called *anisotropic* if is does not contain a non trivial split torus. Any torus C/K contains a maximal split torus S/K and a maximal anisotropic torus $C_1//K$. The multiplication induces a map

$$m : S \times C_1 \to C$$

this is a surjective (in the sense of algebraic groups) homomorphism whose kernel is a finite algebraic group. We call such map an *isogeny* and write that $C = S \cdot C_1$.

We give an example. Our torus $R_{L/\mathbb{Q}}(\mathbb{G}_m/L)$ contains $\mathbb{G}_m/\mathbb{Q}$ as a subtorus: For any ring R containing $\mathbb{Q}$ we have $R^\times = \mathbb{G}_m(R) \in (\mathbb{R} \otimes L)^\times$. On the other and we have the norm map $N_{L/\mathbb{Q}} : (\mathbb{R} \otimes L)^\times \to R^\times$ and the kernel defines a subgroup

$$R^{(1)}_{L/\mathbb{Q}}(\mathbb{G}_m/L) \subset R_{L/\mathbb{Q}}(\mathbb{G}_m/L)$$

and it is clear that

$$m : \mathbb{G}_m \times R^{(1)}_{L/\mathbb{Q}}(\mathbb{G}_m/L) \to R_{L/\mathbb{Q}}(\mathbb{G}_m/L)$$

has a finite kernel which is the finite algebraic group of $[L:\mathbb{Q}]$-th roots of unity.

For any torus $T = \mathbb{G}_m^r$ we define the character module as the group of homomorphisms

$$X^*(T) = \mathrm{Hom}(T, \mathbb{G}_m).. \tag{1.2}$$

If the torus is split, i.e. $T = \mathbb{G}_m^r$ then $X^*(T) = \mathbb{Z}^r$ and the identification is given by $(n_1, n_2, \dots, n_r) \mapsto \{(x_1, x_2, \dots, x_r) \mapsto x_1^{n_1} x_2^{n_2} \dots x_r^{n_r}\}$. We write the group structure on $X^*(T)$ additively, this means that $(\gamma_1 + \gamma_2)(x) = \gamma_(x)\gamma_2(x)$.

It is a theorem that for any torus we can find a finite, separable, normal extension L/K such that $T \times_K L$ splits. Then it is easy to see that we have an action of the Galois group $\mathrm{Gal}(L/K)$ on $X^*(T \times_K L) = \mathbb{Z}^r$. If we have two tori $T_1/K, T_2/K$ which split over L

$$\mathrm{Hom}_K(T_1, T_2) \xrightarrow{\sim} \mathrm{Hom}_{\,\mathrm{Gal}(L/K)}(X^*(T_2 \times_K L), X^*(T_1 \times_K L)) \tag{1.3}$$

To any $\mathrm{Gal}(L/K)-$ action on $\mathbb{Z}^n$ we can find a torus T/K which splits over L and which realizes this action.

A homomorphism $\phi : T_1/K \to T_2$ is called an isogeny if $\dim(T_1) = \dim(T_2)$ and if ${}^t\phi : X^*(T_2) \to X^*(T_1)$ is injective.

Semi-simple groups, reductive groups,.

An important class of linear algebraic groups is formed by the *semisimple* and the *reductive* groups. I do not want to give the precise definition here. Roughly, a linear group is reductive if it does not contain a non trivial normal subgroup which is isomorphic to a product of groups of type G_a. A group is called semisimple, if it is reductive and does not contain a non trivial torus in its centre.

For example the groups Sl_n, Sp_n are semi simple. The groups $\mathrm{SO}(f)$ are semi-simple provided $n \geq 3$. The groups Gl_n and especially the multiplicative group $\mathrm{Gl}_1/\mathbb{Q} = \mathbb{G}_m/\mathbb{Q}$ are reductive.

Any reductive group $G/\mathbb{Q}$ (or over any field of characteristic zero) has a central torus $C/\mathbb{Q}$ and this central torus contains a maximal split torus S. The derived $G^{(1)}/\mathbb{Q}$ is semi simple and we get an isogeny

$$G^{(1)} \times C_1 \times S \to G$$

or briefly $G = G^{(1)} \cdot C_1 \cdot S$.

If for instance $G = \mathbb{R}_{L/\mathbb{Q}}(\mathrm{Gl}_n/L)$ then $G^{(1)} = \mathbb{R}_{L/\mathbb{Q}}(\mathrm{Sl}_n/L)$ and $C = R_{L/\mathbb{Q}}(\mathbb{G}_m/L)$ and this yields the product decomposition up to isogeny

$$G = G^{(1)} \cdot R^{(1)}_{L/\mathbb{Q}}(\mathbb{G}_m/L) \cdot \mathbb{G}_m.$$

1.1.2 k-forms of algebraic groups

Exercise: 1) *Consider the following two quadratic forms over $\mathbb{Q}$:*

$$f(x,y,z) = x^2 + y^2 - z^2\ ,\ f_1(x,y,z) = x^2 + y^2 - 3z^2.$$

Prove that the first form is isotropic. This means there exists a vector $(a, b, c) \in \mathbb{Q}^3 \setminus \{0\}$ *with*

$$f(a, b, c) = 0.$$

Show that the second form is anisotropic, i.e. it has no such vector.

2) Prove that the two linear algebraic group $G/\mathbb{Q} = SO(f)/\mathbb{Q}$ *and* $G_1/\mathbb{Q} = SO(f_1)/\mathbb{Q}$ *cannot be isomorphic. (Hint: This is not so easy since we did not define when two groups are isomorphic.)*

Here is some advice: In general we call an element $e \neq u \in G(\mathbb{Q})$ *unipotent if it is unipotent in* $GL_n(\mathbb{Q})$ *where we consider* $G/\mathbb{Q} \hookrightarrow GL_n/\mathbb{Q}$*. It turns out that this notion of unipotence does not depend on the embedding.*

Now it is possible to show that our first group $G(\mathbb{Q}) = SO(f)(\mathbb{Q})$ *has unipotent elements, and* $G_1(\mathbb{Q})$ *does not. Hence these two groups cannot be isomorphic.*

3) Prove that the two algebraic groups $G \times_{\mathbb{Q}} \mathbb{R}$ *and* $G_1 \times_{\mathbb{Q}} \mathbb{R}$ *are isomorphic, and therefore the two groups* $G(\mathbb{R})$ *and* $G_1(\mathbb{R})$ *are isomorphic.*

In this example we see, that we may have two groups $G/k, G_1/k$ which are not isomorphic but which become isomorphic over some extension L/k. Then we say that the groups are *k-forms* of each other. To determine the different forms of a given group G/k is sometimes difficult one has to use the concepts of Galois cohomology.

For a separable normal extension L/k we have the almost tautological description

$$G(k) = \{g \in G(L) | \sigma(g) = g \text{ for all elements in the Galois group } \quad \mathrm{Gal}(L/k)\}.$$

Now let we can consider the functor $\mathrm{Aut}(G)$: It attaches to any field extension L/k the group of automorphisms $\mathrm{Aut}(G)(L)$ of the algebraic group $G \times_k L$. We denote this action by $g \mapsto \sigma(g) = g^\sigma$. Note that this notation gives us the rule $g^{(\sigma\tau)} = (g^\tau)^\sigma$. A 1-cocycle of $\mathrm{Gal}(L/k)$ with values in $\mathrm{Aut}(G)$ is a map $c : \sigma \mapsto c_\sigma \in \mathrm{Aut}(G)(L)$ which satisfies the cocycle rule

$$c_{\sigma\tau} = c_\sigma c_\tau^\sigma$$

Now we define a new action of $\mathrm{Gal}(L/k)$ on $G(L)$: An element σ acts by

$$g \mapsto c_\sigma g^\sigma g_\sigma^{-1}$$

We define a new algebraic group G_1/k: For any extension E/k we have an action of $\mathrm{Gal}(L/k)$ on $E \otimes_k L$ and we put

$$G_1(E) = \{g \in G(E \otimes_k L) | g = c_\sigma g^\sigma g_\sigma^{-1}\}$$

For the trivial cocycle $\sigma \mapsto 1$ this gives us back the original group.

It is plausible and in fact not very difficult to show that $E \to G_1(E)$ is in fact represented by an algebraic group. This group is clearly a k-form of G/k.

We can define an equivalence relation on the set of cocycles, we say that

$$\{\sigma \mapsto c_\sigma\} \simeq \{\sigma \mapsto c'_\sigma\}$$

if and only if we can find a $a \in G(L)$ such that

$$c'_\sigma = a^{-1} c_\sigma a^\sigma \text{ for all } \sigma \in \mathrm{Gal}(L/k)$$

We define $H^1(L/k, \mathrm{Aut}(G))$ as the set of 1-cocycles modulo this equivalence relation. If we have a larger normal separable extension $L' \supset L \supset k$ then we get an inclusion $H^1(L/k, \mathrm{Aut}(G)) \hookrightarrow H^1(L'/k, \mathrm{Aut}(G))$. If $\bar{k}_s$ is a separable closure of k we can form the limit over all finite extensions $k \subset L \subset \bar{k}_s$ and put

$$H^1(\bar{k}_s/k, \mathrm{Aut}(G)) = \lim_{\rightarrow} H^1(L/k,\ \mathrm{Aut}(G))$$

This set is isomorphic to the set of isomorphism classes of k-forms of G/k.

We may apply the same concepts in a slightly different situation. A $k-$algebra D over the field k is called a central simple algebra, if it has a unit element $\neq 0$, if it is finite dimensional over k, if its centre is k (embedded via the unit element) and if it has no non trivial two sided ideals. It is a classical theorem, that such an algebra over a separably closed field is isomorphic to a full matrix algebra $M_n(k)$. Hence we can say over an arbitrary field k, that the central simple algebra of dimension n^2 are the k-forms of $M_n(k)$.

For any algebraic group G/k we may consider the adjoint group $\mathrm{Ad}(G)$, this is the quotient of G/k by its center. It can be shown, that this is again an algebraic group over k. It is clear that we have an embedding

$$\mathrm{Ad}(G) \to\ \mathrm{Aut}(G)$$

which for any $g \in \mathrm{Ad}(G)(L)$ is given by

$$g \mapsto \{x \mapsto g^{-1}xg\}.$$

A form G_1/k of a group G/k is called an *inner k-form*, if it is in the image of

$$H^1(\bar{k}_s/k, \mathrm{Ad}(G)) \to H^1(\bar{k}_s/k, \mathrm{Aut}(G)).$$

We call a semi simple group G/k *anisotropic* if it does not contain a non trivial split torus (See exercise 1.2.1.) In our example below the group of elements of norm 1 is semi simple and anisotropic if and only if $D(a,b)$ is a field.

I want to give an example, we consider the algebraic group $\mathrm{Gl}_2/\mathbb{Q}$ we consider two integers $a, b \neq 0$, for simplicity we assume that b is not a square. Then we have the quadratic extension $L = \mathbb{Q}(\sqrt{b})$. The element $\begin{pmatrix} 0 & a \\ 1 & 0 \end{pmatrix}$ defines the inner automorphism

$$\mathrm{Ad}(\begin{pmatrix} 0 & a \\ 1 & 0 \end{pmatrix}) : g \mapsto \begin{pmatrix} 0 & a \\ 1 & 0 \end{pmatrix} g \begin{pmatrix} 0 & a \\ 1 & 0 \end{pmatrix}^{-1}$$

of the group Gl_2, let σ be its non trivial automorphism. Then $\sigma \mapsto \mathrm{Ad}(\begin{pmatrix} 0 & a \\ 1 & 0 \end{pmatrix})$ and $\mathrm{Id}_{\mathrm{Gal}(L/k)} \mapsto \mathrm{Id}_{\mathrm{Aut}(\ \mathrm{Gl}_2)(L)}$ is a 1-cocycle and we get a $\mathbb{Q}$ form of our group.

Hence we get a $\mathbb{Q}$ form $G_1 = G(a,b)/\mathbb{Q}$ of our group Gl_2. It is an inner form.

Now we can see easily that group of rational points of our above group $G(a,b)(\mathbb{Q})$ is the multiplicative group of a central simple algebra $D(a,b)/\mathbb{Q}$. To get this algebra we consider the algebra $M_2(L)$ of (2,2)-matrices over L. We define

$$D(a,b)=\{x\in M_2(L)|x=\mathrm{Ad}(\begin{pmatrix}0&a\\1&0\end{pmatrix})x^\sigma\mathrm{Ad}(\begin{pmatrix}0&a\\1&0\end{pmatrix})^{-1}\}.$$

We have an embedding of the field L into this algebra, which is given by

$$u\mapsto\begin{pmatrix}u&0\\0&u^\sigma\end{pmatrix}$$

Let u_b the image of $\sqrt{b}$ under this map. We also have the element $u_a=\begin{pmatrix}0&a\\1&0\end{pmatrix}$ in this algebra.

Now I leave it as an exercise to the reader that as a $\mathbb{Q}$ vctor space

$$D(a,b)=\mathbb{Q}\oplus\mathbb{Q}u_b\oplus\mathbb{Q}u_a\oplus\mathbb{Q}u_au_b$$

We have the relation $u_a^2=a, u_b^2=b, u_au_b=-u_bu_a$.

Of course we should ask ourselves: When is $D(a,b)$ split, this means isomorphic to $M_2(\mathbb{Q})$. To answer this question we consider the norm homomorphism, which is defined by

$$x+yu_b+zu_a+wa_au_b\mapsto(x+yu_b+zu_a+wa_au_b)(x-yu_b-zu_a-wa_au_b)=x^2-y^2b-z^2a+w^2ab.$$

It is easy to see that $D(a,b)$ splits if and only if we can find a non zero element whose norm is zero.

If we do this with $\mathbb{R}$ as base field and if we take $a=-1,b=-1$ then we get the Hamiltonian quaternions, which is non split.

We may also look at the p-adic completions $\mathbb{Q}_p$ of our field. Then it is not difficult to see that $D(a,b)$ splits over $\mathbb{Q}_p$ if $p\neq 2$ and $p\nmid ab$. Hence it is clear that there is only a finite number of primes p for which $D(a,b)$ does not split.

If we consider $\mathbb{R}$ as completion at the infinite place, and the $\mathbb{Q}_p$ as the completions at the finite places, then we have

The algebra $D(a,b)$ splits if and only if it splits at all places. The number of places where it does not split is always even.

The first assertion is the so called Hasse-Minkowski principle, the second assertion is essentially equivalent to the quadratic reciprocity law.

1.1.3 The Lie-algebra

We need some basic facts about the Lie-algebras of algebraic groups.

For any algebraic group G/k we can consider its group of points with values in $k[\epsilon]=k[X]/(X^2)$. We have the homomorphism $k[\epsilon]\to k$ sending ϵ to zero and hence we get an exact sequence

$$0\to\mathfrak{g}\to G(k[\epsilon])\to G(k)\to 1.$$

The kernel $\mathfrak{g}$ is a k-vector space, if the characteristic of k is zero, then its dimension is equal to the dimension of G/k. It is denoted by $\mathfrak{g}=\mathrm{Lie}(G)$.

Let us consider the example of the group $G = SO(f)$, where $f : V\times \to k$ is a non degenerate symmetric bilinear form. In this case an element in $G(k[\epsilon])$ is of the form $\mathrm{Id} + \epsilon A, A \in \mathrm{End}(V)$ for which

$$f((\mathrm{Id} + \epsilon A)v, (\mathrm{Id} + \epsilon A)w) = f(v, w)$$

for all $v, w \in V$. Taking into account that $\epsilon^2 = 0$ we get

$$\epsilon(f(Av, w) + f(v, Aw)) = 0,$$

i.e. A is skew with respect to the form, and $\mathfrak{g}$ is the k-vector space of skew endomorphisms. If we give V a basis and if $f = \sum x_i^2$ with respect to this basis then this means the the matrix of A is skew symmetric.

If we consider $G = \mathrm{Gl}_n/k$ then $\mathfrak{g} = M_n(k)$, the Lie-bracket is given by

$$(A, B) \mapsto AB - BA \tag{1.4}$$

We have some kind of a standard basis for our Lie algebra

$$\mathfrak{g} = \bigoplus_{i=1}^{n} kH_i \oplus \bigoplus_{i,j,i\neq j} kE_{i,j} \tag{1.5}$$

where H_i (resp.$E_{i,j}$) are the matrices

$$H_i = \begin{pmatrix} 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & \ddots & & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \dots & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \text{ resp. } E_{i,j} = \begin{pmatrix} 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & \ddots & & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \dots & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

and the only non zero entries (=1) is at (i, i) on the diagonal (resp. and (i, j) off the diagonal.)

For the group Sl_n/k the Lie-algebra is $\mathfrak{g}^{(0)} = \{A \in M_n(k) |\ \mathrm{tr}(A) = 0\}$ and again we have a standard basis

$$\mathfrak{g}^{(0)} = \bigoplus_{i=1}^{n-1} k(H_i - H_{i+1}) \oplus \bigoplus_{i,j,i\neq j} kE_{i,j} \tag{1.6}$$

A *representation* of a group scheme G/k is a k-homomorphism

$$\rho : G \to \mathrm{Gl}(V)$$

where V/k is a $k-$ vector space. Then it is clear from our considerations above that we have a "derivative" of the representation

$$d\rho : \mathfrak{g} = \mathrm{Lie}(G/k) \to \mathrm{Lie}(\mathrm{Gl}(V)) = \mathrm{End}(V)$$

this is k-linear.

Every group scheme G/k has a very special representation, this is the the *Adjoint representation.* We observe that the group acts on itself by conjugation, this is the morphism

$$Inn : G \times_k G \to G$$

which on T valued points is given by

$$Inn(g_1, g_2) \mapsto g_1 g_2 (g_1)^{-1}.$$

This action clearly induces a representation

$$\mathrm{Ad} : G/k \to \mathrm{Gl}(\mathfrak{g})$$

and this is the adjoint representation. This adjoint representation has a derivative and this is a homomorphism of k vector spaces

$$D_{\mathrm{Ad}} = \mathrm{ad} : \mathfrak{g} \to \ \mathrm{End}(\mathfrak{g}).$$

We introduce the notation: For $T_1, T_2 \in \mathfrak{g}$ we put

$$[T_1, T_2] := \mathrm{ad}(T_1)(T_2).$$

Now we can state the famous and fundamental result

Theorem 1.1.1. *The map $(T_1, T_2) \mapsto [T_1, T_2]$ is bilinear and antisymmetric. It induces the structure of a Lie-algebra on $\mathfrak{g}$, i.e. we have the Jacobi identity*

$$[T_1, [T_2, T_3]] + [T_2, [T_3, T_1]] + [T_3, [T_1, T_2]] = 0.$$

We do not prove this here. In the case $G/k = \mathrm{Gl}(V)$ and $T_1, T_2 \in \mathrm{Lie}(\mathrm{Gl}(V) = \mathrm{End}(V)$ we have $[T_1, T_2] = T_1T_2 - T_2T_1$ and in this case the Jacobi Identity is a well known identity.

On any Lie algebra we have a symmetric bilinear form (the Killing form)

$$B : \mathfrak{g} \times \mathfrak{g} \to k \tag{1.7}$$

which is defined by the rule

$$B(T_1, T_2) = \mathrm{trace}(\mathrm{ad}(T_1) \circ \mathrm{ad}(T_2))$$

A simple computation shows that for the examples $\mathfrak{g} = \mathrm{Lie}(\mathrm{Gl}_n)$ and $\mathfrak{g}^{(0)} = \mathrm{Lie}(\mathrm{Sl}_n)$ we have

$$B(T_1, T_2) = 2n\ \mathrm{tr}(T_1T_2) - 2\ \mathrm{tr}(T_1)\ \mathrm{tr}(T_2) \tag{1.8}$$

we observe that in case that one of the T_i is central, i.e.= $u\mathrm{Id}$ we have $B(T_1, T_2) = 0$. In the case of $\mathfrak{g}^{(0)}$ the second term is zero.

It is well known that a linear algebraic group is semi-simple if and only if the Killing form B on its Lie algebra is non degenerate.

1.1.4 Structure of semisimple groups over $\mathbb{R}$ and the symmetric spaces:

We need some information concerning the structure of the group $G_\infty = G(\mathbb{R})$ for semisimple groups over $G/\mathbb{R}$. We will provide this information simply by discussing a series of examples.

Of course the group $G(\mathbb{R})$ is a topological group, actually it is even a Lie group. This means it has a natural structure of a $\mathcal{C}_\infty$ -manifold with respect to this structure. Instead of $G(\mathbb{R})$ we will very often write G_∞. Let G_∞^0 be the connected component of the identity in G_∞. It is an open subgroup of finite index. We will discuss the

Theorem of E. Cartan: *The group G_∞^0 always contains a maximal compact subgroup $K \subset G_\infty^0$ and all maximal compact subgroups are conjugate under G_∞^0. The quotient space $X = G_\infty^0/K$ is again a $\mathcal{C}_\infty$-manifold. It is diffeomorphic to an $\mathbb{R}^n$ and carries a Riemannian metric which is invariant under the operation of G_∞^0 from the left. It has negative sectional curvature. The maximal compact subgroup $K \subset G_\infty^0$ is connected and equal to its own normalizer. Therefore the space X can be viewed as the space maximal compact subgroups in G_∞^0.*

This theorem is fundamental. To illustrate this theorem we consider a series of examples:

The groups $\mathrm{Sl}_d(\mathbb{R})$ and $\mathrm{Gl}_n(\mathbb{R})$:

The group $\mathrm{Sl}_d(\mathbb{R})$ is connected. If $K \subset \mathrm{Sl}_d(\mathbb{R})$ is a closed compact subgroup, then we can find a positive definite quadratic form

$$f : \mathbb{R}^n \to \mathbb{R},$$

such that $K \subset SO(f, \mathbb{R})$. since the group $SO(f, \mathbb{R})$ itself is compact, we have equality. Two such forms f_1, f_2 define the same maximal compact subgroup if thre is a $\lambda > 0$ in $\mathbb{R}$ such that $\lambda f_1 = f_2$.

This is rather clear, if we believe the first assertion about the existence of f. The existence of f is also easy to see if one believes in the theory of integration on K. This theory provides a positive invariant integral

$$\begin{array}{ccc} \mathcal{C}_c(K) & \longrightarrow & \mathbb{R} \\ \varphi & \longrightarrow & \displaystyle\int\limits_K \varphi(k)dk \end{array}$$

with $\int \varphi > 0$ if $\varphi \geq 0$ and not identically zero (positivity), $\int \varphi(kk_0)dk = \int \varphi(k_0k)dk = \int \varphi(k)dk$ (invariance).

To get our form f we start from any positive definite form f_0 on $\mathbb{R}^n$ and put

$$f(\underline{x}) = \int_K f_0(k\underline{x})dk.$$

A positive definite quadratic form on $\mathbb{R}^n$ is the same as a symmetric positive definite bilinear form. Hence the space of positive definite forms is the same as the space of positive definite symmetric matrices

$$\tilde{X} = \left\{ A = (a_{ij}) \mid A =^t A, A > 0 \right\}.$$

Hence we can say that the space of maximal compact subgroups in $\mathrm{Sl}_d(\mathbb{R})$ is given by

$$X = \tilde{X}/\mathbb{R}^*_{>0}.$$

It is easy to see that a maximal compact subgroup $K \subset \mathrm{Sl}_d(\mathbb{R})$ is equal to its own normalizer (why?). If we view X as the space of positive definite symmetric matrices with determinant equal to one, then the action of $\mathrm{Sl}_d(\mathbb{R})$ on $X = \mathrm{Sl}_d(\mathbb{R})/K$ is given by

$$(g, A) \longrightarrow g\ A\ {}^t g,$$

and if we view it as the space of maximal compact subgroups, then the action is conjugation.

There is still another interpretation of the points $x \in X$. In our above interpretation a point was a symmetric, positive definite bilinear form $<\ ,\ >_x$ on $\mathbb{R}^n$ up to a homothety. This bilinear form defines a transpose $g \mapsto^{t_x} g$ and hence an involution

$$\Theta_x : g \mapsto ({}^{t_x} g)^{-1} \tag{1.9}$$

Then the corresponding maximal compact subgroup is

$$K_x = \{g \in \mathrm{Sl}_n(\mathbb{R}) | \Theta_x(g) = g\} \tag{1.10}$$

This involution Θ_x is a Cartan involution, it also induces an involution also called Θ_x on the Lie-algebra and it has the property that (See 6.4)

$$(u, v) \mapsto B(u, \Theta_x(v)) = B_{\Theta_x}(u, v) \tag{1.11}$$

is negative definite. This bilinear form is K_x invariant. All these Cartan involutions are conjugate.

If we work with $\mathrm{Gl}_n(\mathbb{R})$ instead then we have some freedom to define the symmetric space. In this case we have the non trivial center $\mathbb{R}^\times$ and it is sometimes useful to define

$$X = \mathrm{Gl}_n(\mathbb{R})/\mathrm{SO}(\mathbb{R}) \cdot \mathbb{R}^\times_{>0} \tag{1.12}$$

then our symmetric space has two components, a point is pair (Θ_x, ϵ) where ϵ is an orientation. If we do not divide by $\mathbb{R}^\times_{>0}$ then we multiply the Riemannian manifold X by a flat subspace and we get the above space $\tilde{X}$.

A Cartan involution on $\mathrm{Gl}_n(\mathbb{R})$ is an involution which induces a Cartan involution on $\mathrm{Sl}_n(\mathbb{R})$ and which is trivial on the center.

Proposition 1.1.1. *The Cartan involutions on* $\mathrm{Gl}_n(\mathbb{R})$ *are in one to one correspondence to the euclidian metrics on* $\mathbb{R}^n$ *up to conformal equivalence.*

Finally we recall the Iwasawa decomposition. Inside $\mathrm{Gl}_n(\mathbb{R})$ we have the standard Borel- subgroup $B(\mathbb{R})$ of upper triangular matrices and it is well known that

$$\mathrm{Gl}_n(\mathbb{R}) = B(\mathbb{R}) \cdot \mathrm{SO}(\mathbb{R}) \cdot \mathbb{R}^\times_{>0} \tag{1.13}$$

and hence we see that $B(\mathbb{R})$ acts transitively on X.

The Arakelow- Chevalley scheme $(\mathrm{Gl}_n/\mathbb{Z}, \Theta_0)$

We consider the case $G = \mathrm{Gl}_n$ and the special Cartan involution $\Theta_0(g) = ({}^t g)^{-1}$ and look at it from a slightly different point of view.

We start from the free lattice $L = \mathbb{Z}e_1 \oplus \mathbb{Z}e_2 \oplus \cdots \oplus \mathbb{Z}e_n$ and we think of $\mathrm{Gl}_n/\mathbb{Z}$ as the scheme of automorphism of this lattice. If we choose an euclidian metric $<\,,\,>$ on Ł $\otimes \mathbb{R}$ then we call the pair $(L, <\,,\,>)$ an Arakelow vector bundle. up to homothety, we get a Cartan involution Θ on $\mathrm{Gl}_n(\mathbb{R})$. We choose the standard euclidian metric with respect to the given basis, i.e. $< e_i, e_j >= \delta_{i,j}$. The the resulting Cartan involution is the standard one: $\Theta_0 : g \mapsto ({}^t g)^{-1}$. This pair $(\mathrm{Gl}_n/\mathbb{Z}, \Theta_0)$ is called an Arakelow- Chevalley scheme. (In a certain sense the integral structure of $\mathrm{Gl}_n/\mathbb{Z}$ and the choice of the Cartan involution are "optimally adapted")

In this case we find for our basis elements in (1.5)

$$B_{\Theta_0}(H_i, H_j) = -2n\delta_{i,j} + 2; B_{\Theta_0}(E_{i,j}, E_{k,l}) = -2n\delta_{i,k}\delta_{j,l} \tag{1.14}$$

hence the $E_{i,j}$ are part of an orthonormal basis.

We propose to call a pair $(L, <\,,\,>_x)$ an Arakelow vector bundle over $\mathrm{Spec}(\mathbb{Z}) \cup \{\infty\}$ and $(\mathrm{Gl}_n, \Theta_x)$ an Arakelow group scheme. The Arakelow vector bundles modulo conformal equivalence are in one-to one correspondence with the Arakelow group schemes of type Gl_n.

The group $\mathbf{Sl}_d(\mathbb{C})$

We now consider the group $G/\mathbb{R}$ whose group of real points is $G(\mathbb{R}) = \mathrm{Sl}_d(\mathbb{C})$ (see 1.1 example 4)).

A completely analogous argument as before shows that the maximal compact subgroups are in one to one correspondence to the positive definite hermitian forms on $\mathbb{C}^n$ (up to multiplication by a scalar). Hence we can identify the space of maximal compact subgroup $K \subset G(\mathbb{R})$ to the space of positive definite hermitian matrices

$$X = \left\{ A \mid A = {}^t\overline{A}\,,\ A > 0\,,\ \det A = 1 \right\}.$$

The action of $\mathrm{Sl}_d(\mathbb{C})$ by conjugation on the maximal compact subgroups becomes

$$A \longrightarrow g\ A\ {}^t\overline{g}$$

on the space of matrices.

The orthogonal group:

The next example I want to discuss is the example of an orthogonal group of a quadratic form

$$f(x_1, \ldots, x_n) = x_1^2 + \ldots + x_m^2 - x_{m+1}^2 - \ldots - x_n^2.$$

Since at this point we consider only groups over the real numbers, we may assume that our form is of this type.

In this case one has the usual notation

$$SO(f, \mathbb{R}) = SO(m, n-m).$$

Of course we can use the same argument as before and see that for any maximal compact subgroup $K \subset SO(f, \mathbb{R})$ we may find a positive definite form ψ

$$\psi : \mathbb{R}^n \longrightarrow \mathbb{R}$$

such that $K = SO(f, \mathbb{R}) \cap SO(\psi, \mathbb{R})$. But now we cannot take all forms ψ, i.e. only special forms ψ provide maximal compact subgroup.

We leave it to the reader to verify that any compact subgroup K fixes an orthogonal decomposition $\mathbb{R}^n = V_+ \oplus V_-$ where our original form f is positive definite on V_+ and negative definite on V_-. Then we can take a ψ which is equal to f on V_+ and equal to $-f$ on V_-.

Exercise 3 *a) Let $V/\mathbb{R}$ be a finite dimensional vector space and let f be a symmetric non degenerate form on V. Let $K \subset SO(f)$ be a compact subgroup. If f is not definite then the action of K on V is not irreducible.*

b) We can find a K invariant decomposition $V = V_- \oplus V_+$ such that f is negative definite on V_- and positive definite on V_+

In this case the structure of the quotient space $G(\mathbb{R})/K$ is not so easy to understand. We consider the special case of the form

$$x_1^2 + \ldots + x_n^2 - x_{n+1}^2 = f(x_1, \ldots, x_{n+1}).$$

We consider in $\mathbb{R}^{n+1}$ the open subset

$$X_- = \{v = (x_1 \ldots x_{n+1}) \mid f(v) < 0\}.$$

It is clear that this set has two connected components, one of them is

$$X_-^+ = \{v \in X_- \mid x_{n+1} > 0\}$$

Since it is known that $SO(n,1)$ acts transitively on the vectors of a given length, we find that $SO(n,1)$ cannot be connected. Let $G_\infty^0 \subset SO(n,1)$ be the subgroup leaving X_-^+ invariant.

Now it is not to difficult to show that for any maximal compact subgroup $K \subset G_\infty^0$ we can find a ray $\mathbb{R}_{>0}^* \cdot v \subset X_-^{(+)}$ which is fixed by K.

(Start from $v_0 \in X_-^{(+)}$ and show that $R_{>0}^* K v_0$ is a closed convex cone in $X_-^{(+)}$. It is K invariant and has a ray which has a "centre of gravity" and this is fixed under K.)

For a vector $v = (x_1, \ldots, x_{n+1}) \in X_-^{(+)}$ we may normalize the coordinate x_{n+1} to be equal to one; then the rays $\mathbb{R}_{>0}^+ v$ are in one to one correspondence with the points of the ball

$$\overset{\circ}{D}_n = \left\{(x_1, \ldots, x_n) \mid x_1^2 + \ldots + x_n^2 < 1\right\} \subset X_-^{(+)}.$$

This tells us that we can identify the set of maximal compact subgroups $K \subset G_\infty^0$ with the points of this ball. The first conclusion is that $G_\infty^0/K \simeq D^n$ is topologically a cell (diffeomorphic to $\mathbb{R}^n$). Secondly we see that for a $v \in X_-^+$ we have an orthogonal decompositon with respect to f

$$\mathbb{R}^{n+1} = \langle v \rangle + \langle v \rangle^\perp,$$

and the corresponding maximal compact subgroup is the orthogonal group on $\langle v \rangle^\perp$.

Special low dimensional cases

1) We consider the group $\mathrm{Sl}_2(\mathbb{R})$. It acts on the upper half plane

$$H = \{z \mid z \in \mathbb{C}, \Im(z) > 0\}$$

by

$$(g, z) \longrightarrow \frac{az+b}{cz+b}, \qquad g = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{Sl}_2(\mathbb{R}).$$

It is clear that the stabilizer of the point $i \in H$ is the standard maximal compact subgroup

$$K = SO(2) = \left\{ \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix} \right\}.$$

Hence we have $H = \mathrm{Sl}_2(\mathbb{R})/K$. But this quotient has been realized as the space of symmetric positive definite 2×2-matrices with determinant equal to one

$$x = \left\{ \begin{pmatrix} y_1 & x_1 \\ x_1 & y_2 \end{pmatrix} \mid y_1 y_2 - x_1^2 = 1, y_1 > 0 \right\}.$$

It is clear how to find an isomorphism between these two explicit realizations. The map

$$\begin{pmatrix} y_1 & x_1 \\ x_1 & y_2 \end{pmatrix} \longrightarrow \frac{i + x_1}{y_2},$$

is compatible with the action of $\mathrm{Sl}_2(\mathbb{R})$ on both sides and sends the identity $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ to the point i.

If we start from a point $z \in H$ the corresponding metric is as follows: We identify the lattices $\langle 1, z\rangle = \{a + bz \mid a, b \in \mathbb{Z}\} = \Omega$ to the lattice $\mathbb{Z}^2 \subset \mathbb{R}^2$ by sending $1 \to \binom{1}{0}$ and $z \to \binom{0}{1}$. The standard euclidian metric on $\mathbb{C} = \mathbb{R}^2$ induces a metric on $\Omega \subset \mathbb{C}$, and this metric is transported to $\mathbb{R}^2$ by the identification $\Omega \otimes \mathbb{R} \to \mathbb{R}^2$.

2) The two groups $\mathrm{Sl}_2(\mathbb{R})$ and $P\mathrm{Sl}_2(\mathbb{R}) = \mathrm{Sl}_2(\mathbb{R})/\{\pm \mathrm{Id}\}$ give rise to the same symmetric space. The group $P\mathrm{Sl}_2(\mathbb{R})$ acts on the space $M_2(\mathbb{R})$ of 2×2-matrices by conjugation (the group $\mathrm{Gl}_2(\mathbb{R})$ acts by conjugation and the centre acts trivially) and leaves invariant the space

$$\{A \in M_2(\mathbb{R}) \mid \mathrm{trace}(A) = 0\} = M_2^0(\mathbb{R}).$$

On this three-dimensional space we have a symmetric quadratic form

$$\begin{aligned} B &: M_2^0(\mathbb{R}) \longrightarrow \mathbb{R} \\ B &: A \longrightarrow \frac{1}{2} \text{ trace } (A^2) \end{aligned}$$

and with respect to the basis $h = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$, $e_+ = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $e_- = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$, this form is $x_1^2 + x_2^2 - x_3^2$.

Hence we see that $SO(M_2^0(\mathbb{R}), B) = SO(2,1)$, and hence we have an isomorphism between $P\mathrm{Sl}_2(\mathbb{R})$ and the connected component of the identity $G_\infty^0 \subset$

$SO(2,1)$. Hence we see that our symmetric space $H = \mathrm{Sl}_2(\mathbb{R})/K = P\mathrm{Sl}_2(\mathbb{R})/\overline{K}$ can also be realized (see ....) as disc

$$D = \{(x_1, x_2) \mid x_1^2 + x_2^2 < 1\}$$

where we normalized $x_3 = 1$ on $X_-^{(+)}$ as in ....

The group $\mathbf{Sl}_2(\mathbb{C})$.

Recall that in this case the symmetric space is given by the positive definite hermitian matrices

$$A = \left\{ \begin{pmatrix} y_1 & z \\ \overline{z} & y_2 \end{pmatrix} \mid \det(A) = 1, y_1 > 0 \right\}.$$

In this case we have also a realization of the symmetric space as an upper half space. We send

$$\begin{pmatrix} y_1 & w \\ \overline{w} & y_2 \end{pmatrix} \longmapsto \left(\frac{w}{y_2}, \frac{1}{y_2} \right) = (z, \zeta) \in \mathbb{C} \times \mathbb{R}_{>0}$$

The inverse of this isomorphism is given by

$$(z, \zeta) \mapsto \begin{pmatrix} \zeta + z\overline{z}/\zeta & z/\zeta \\ \overline{z}/\zeta & 1/\zeta \end{pmatrix}$$

As explained earlier, the action of $\mathrm{Gl}_2(\mathbb{C})$ on the maximal compact subgroup given by conjugation yields the action

$$G(\mathbb{R}) \times X \longrightarrow X,$$

$$(g, A) \longrightarrow gA^t\overline{g},$$

on the hermitian matrices. Translating this into the realization as an upper half space yield the slightly scaring formula

$$\begin{aligned} G \times (\mathbb{C} \times \mathbb{R}_{>0}) &\longrightarrow \mathbb{C} \times \mathbb{R}_{>0}, \\ (g, (z, \zeta)) &\longrightarrow \left(\frac{(az+b)\,\overline{(cz+d)} + a\overline{c}\,\zeta^2}{(cz+d)\,\overline{(cz+d)} + c\overline{c}\,\zeta^2}\ ,\ \frac{\zeta}{(cz+d)\,\overline{(cz+d)} + c\overline{c}\,\zeta^2} \right) \end{aligned}$$

1.3.4. The Riemannian metric: It was already mentioned in the statement of the theorem of Cartan that we always have a G_∞^0 invariant Riemannian metric on X. It is not to difficult to construct such a metric which in many cases is rather canonical.

In the general case we observe that the maximal compact subgroup is the stabilizer of the point $x_0 = e \cdot K \in G_\infty^0/K = X$. Hence it acts on the tangent space of x_0, and we can construct a k-invariant positive definite quadratic form on this tangent sapce. Then we use the action of G_∞^0 on X to transport this metric to an arbitrary point in X: If $x \in X$ we find a g so that $x = gx_0$, it defines an isomorphism between the tangent space at x_0 and the tangent space at x. Hence we get a form on the tangent space at x, which will not depend on the choice of $g \in G_\infty^0$.

In our examples this metric is always unique up to scalars.

a) In the case of the group $\mathrm{Sl}_d(\mathbb{R})$ we may take as a base point $x_0 \in X$ the identity $\mathrm{Id} \in \mathrm{Sl}_d(\mathbb{R})$. The corresponding maximal compact subgroup is the orthogonal group $SO(n)$. The tangent space at Id is given by the space

$$\mathrm{Sym}_n^0(\mathbb{R}) = T_{\mathrm{Id}}^X$$

of symmetric matrices with trace zero. On this space we have the form

$$Z \longrightarrow \mathrm{trace}(Z^2),$$

which is positive definite (a symmetric matrix has real eigenvalues). It is easy to see that the orthogonal group acts on this tangent space by conjugation, hence the form is invariant.

b) A similar argument applies to the group $G_\infty = \mathrm{Sl}_d(\mathbb{C})$. Again the identity Id is a nice positive definite hermitian matrix. The tangent space consists of the hermitian matrices

$$T_{\mathrm{Id}}^X = \left\{ A \mid A =^t \overline{A} \text{ and } \mathrm{tr}(A) = 0 \right\},$$

and the invariant form is given by

$$A \longrightarrow \mathrm{tr}(A\overline{A}).$$

c) In the case of the group $G_\infty^0 \subset SO(f)$ where f is the quadratic form

$$f(x_1, \ldots, x_{n+1}) = x_1^2 + \ldots + x_n^2 - x_{n+1}^2.$$

We realized the symmetric space as the open ball

$$\overset{\circ}{D}_n = \{(x_1, \ldots, x_n) \mid x_1^2 + \ldots + x_n^2 < 1\}.$$

The orthogonal group $SO(n,1)$ is the stabilizer of $0 \in \overset{\circ}{D}_n$, and hence it is clear that the Riemannian metric has to be of the form

$$h(x_1^2 + \ldots + x_n^2)(dx_1^2 + \ldots dx_n^2)$$

(in the usual notation). A closer look shows that the metrics has to be

$$\frac{dx_1^2 + \ldots + dx_n^2}{\sqrt{1 - x_1^2 - \ldots - x_n^2}}.$$

In our two low dimensional spacial examples the metric is easy to determine. For the action of the group $\mathrm{Sl}_2(\mathbb{R})$ on the upper half plane H we observe that for any point $z_0 = x + iy \in H$ the tangent vectors $\frac{\partial}{\partial x}|_{z_0}, \frac{\partial}{\partial y}|_{z_0}$ form a basis of the tangent spaces at z_0.

If we take $z_0 = i$ then the stabilizer is the group $SO(2)$ and for

$$e(\varphi) = \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix}.$$

We have

$$e(\varphi) \cdot \left(\frac{\partial}{\partial x} |_i \right) = \cos 2\varphi \cdot \frac{\partial}{\partial x} |_i + \sin 2\varphi \frac{\partial}{\partial y} |_i$$
$$e(\varphi) \left(\frac{\partial}{\partial y} |_i \right) = \sin 2\varphi \cdot \frac{\partial}{\partial x} |_i + \cos 2\varphi \frac{\partial}{\partial y} |_i.$$

Hence we find that $\frac{\partial}{\partial x}\mid_i$ and $\frac{\partial}{\partial y}\mid_i$ have to be orthogonal and of the same length.

Now the matrix

$$\begin{pmatrix} y & x \\ 0 & 1 \end{pmatrix}$$

sends i into the point $z = x + iy$. It sends $\frac{\partial}{\partial x}\mid_i$ and $\frac{\partial}{\partial y}\mid_i$ into $y \cdot \frac{\partial}{\partial x}\mid_z$ and $y \cdot \frac{\partial}{\partial y}\mid_z$, and hence we must have for our invariant metric

$$\langle \frac{\partial}{\partial x}\mid_z, \frac{\partial}{\partial y}\mid_z\rangle = 0\ ;\ \langle \frac{\partial}{\partial x}\mid_z, \frac{\partial}{\partial x}\mid_z\rangle = \frac{1}{y^2}\ ;\ \langle \frac{\partial}{\partial y}\mid_z, \frac{\partial}{\partial y}\mid_z\rangle = \frac{1}{y^2},$$

and this is in the usual notation the metric

$$ds^2 = \frac{1}{y^2}(dx^2 + dy^2).$$

A completely analogous argument yields for the space $\mathbb{H}_3$ the metric

$$\frac{1}{\zeta^2}\ (d\zeta^2 + dx^2 + dy^2).$$

1.2 Arithmetic groups

If we have a linear algebraic group $G/\mathbb{Q} \hookrightarrow GL_n$ we may consider the group $\Gamma = G(\mathbb{Q}) \cap GL_n(\mathbb{Z})$. This is the first example of an *arithmetic* group. It has the following fundamental property:

Proposition: *The group Γ is a discrete subgroup of the topological group $G(\mathbb{R})$.*

This is rather easily reduced to the fact that $\mathbb{Z}$ is discrete in $\mathbb{R}$. Actually our construction provides a big family of arithmetic groups. For any integer $m > 0$ we have the homomorphism of reduction $\mod m$, namely

$$GL_n(\mathbb{Z}) \longrightarrow GL_n(\mathbb{Z}/m\mathbb{Z}).$$

The kernel $GL_n(\mathbb{Z})(m)$ of this homomorphism has finite indexsx in $GL_n(\mathbb{Z})$ and hence the intersection $\Gamma' = GL_n(\mathbb{Z})(m) \cap \Gamma$ has finite index in Γ.

Definition 2.1.: *A subgroup Γ'' of Γ is called a congruence subgroup, if we can find an integer m such that*

$$GL_n(\mathbb{Z})(m) \cap \Gamma \subset \Gamma'' \subset \Gamma.$$

At this point a remark is in order. I explained already that a linear algebraic group $G/\mathbb{Q}$ may be embedded in different ways into different groups GL_n, i.e.

$$G \begin{array}{l} \hookrightarrow\ GL_{n_1} \\ \\ \hookrightarrow\ GL_{n_2} \end{array}$$

In this case we may get two different congruence subgroups

$$\Gamma_1 = G(\mathbb{Q}) \cap GL_{n_1}(\mathbb{Z}), \Gamma_2 = G(\mathbb{Q}) \cap GL_{n_2}(\mathbb{Z}).$$

It is not hard to show that in such a case we can find an $m > 0$ such that

$$\begin{aligned}\Gamma_1 &\supset \Gamma_2 \cap GL_{n_2}(\mathbb{Z})(m) \\ \Gamma_2 &\supset \Gamma_1 \cap GL_{n_1}(\mathbb{Z})(m) \quad .\end{aligned}$$

From this we conclude that the notion of congruence subgroup does not depend on the way we realized the group $G/\mathbb{Q}$ as a subgroup in the general linear group.

Now we may also define the notion of an *arithmetic* subgroup. A subgroup $\Gamma' \subset G(\mathbb{Q})$ is called arithmetic if for any congruence subgroup $\Gamma \subset G(\mathbb{Q})$ the group $\Gamma' \cap \Gamma$ is of finite index in Γ' and Γ. (We say that Γ' and Γ are commensurable.) By definition all congruence subgroups are arithmetic subgroups.

The most prominent example of an arithmetic group is the group

$$\Gamma = \mathrm{Sl}_2(\mathbb{Z}).$$

Another example is obtained as follows. We defined for any number field $K/\mathbb{Q}$ the group

$$G/\mathbb{Q} = R_{K/\mathbb{Q}}(\mathrm{Sl}_d)$$

for which $G(\mathbb{Q}) = \mathrm{Sl}_d(K)$. If $\mathcal{O}_K$ is the ring of integers in K, then $\Gamma = \mathrm{Sl}_d(\mathcal{O}_K)$ (and also $\tilde{\Gamma} = GL_n(\mathcal{O}_K)$) is a congruence (and hence arithmetic) subgroup of $G(\mathbb{Q})$.

It is very interesting that the groups $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$ and $\mathrm{Sl}_2(\mathcal{O}_K)$ for imaginary quadratic $K/\mathbb{Q}$ always contain arithmetic subgroups $\Gamma' \subset \Gamma$ which are not congruence subgroups. This means that in general the class of arithmetic subgroups is larger than the class of congruence subgroups. We will prove this assertion in (See ......).

If only the group $G(\mathbb{R})$ is given (as the group of real points of a group $G/\mathbb{Q}$ or perhaps only as a Lie group, then the notion of arithmetic group $\Gamma \subset G(\mathbb{R})$ is not defined. The notion of an arithmetic subgroup $\Gamma \subset G(\mathbb{R})$ requires the choice of a group scheme $G/\mathbb{Q}$ such that the group $G(\mathbb{R})$ is the group of real points of this group over $\mathbb{Q}$. The exercise in 1.1.2. shows that different $\mathbb{Q}$- forms provide different arithmetic groups.

Exercise 2 *If $\gamma \in GL_n(\mathbb{Z})$ is a nontrivial torsion element and if $\gamma \equiv \mathrm{Id} \mod m$ then $m = 1$ or $m = 2$. In the latter case the element γ is of order 2. This implies that for $m \geq 3$ the congruence subgroup $GL_n(\mathbb{Z})(m)$ of $GL_n(\mathbb{Z})$ is torsion free.*

This implies of course that any arithmetic group has a subgroup of finite index, which is torsion free.

1.2.1 The locally symmetric spaces

We start from a semisimple group $G/\mathbb{Q}$. To this group we attached the the group of real points $G(\mathbb{R}) = G_\infty$. In G_∞ we have the connected component G^0_∞ of the identity and in this group we choose a maximal compact subgroup K. The quotient space $X = G_\infty/K$ is a symmetric space which now may have several connected components. On this space we have the action of an arithmetic group Γ.

We have a fundamental fact:

The action of Γ on X is properly discontinuous, i.e. for any point $x \in X$ there exists an open neighborhood U_x such that for all $\gamma \in \Gamma$ we have

$$\gamma U_x \cap U_x = \emptyset \quad \text{or} \quad \gamma x = x.$$

Moreover for all $x \in X$ the stabilizer

$$\Gamma_x = \{\gamma \mid \gamma x = x\}$$

is finite.

This is easy to see: If we consider the projection $p : G(\mathbb{R}) \to G(\mathbb{R})/K = X$, then the inverse image $p^{-1}(U_x)$ of a relatively compact neighborhood U_x of $x = g_0 K$ is of the form $V_{g_0} \cdot K$, where V_{g_0} is a relatively compact neighborhood of g_0. Hence we look for the solutions of the equation

$$\gamma v k = v' k', \gamma \in \Gamma, v, v' \in V_{g_0}, k, k' \in K.$$

Since Γ is discrete in $G(\mathbb{R})$ there are only finitely many possibilities for γ and they can be ruled out by shrinking U_x with the exception of those γ for which $\gamma x = x$.

If Γ has no torsion then the projection

$$\pi : X \longrightarrow \Gamma\backslash X$$

is locally a $\mathcal{C}_\infty$-diffeomorphism. To any point $x \in \Gamma\backslash X$ and any point $\tilde{x} \in \pi^{-1}(x)$ we find a neighborhood $U_{\tilde{x}}$ such that

$$\pi : U_{\tilde{x}} \xrightarrow{\sim} U_x.$$

Hence the space $\Gamma\backslash X$ inherits the Riemannian metric and the quotient space is a locally symmetric space.

If our group Γ has torsion, then a point $\tilde{x} \in X$ may have a nontrivial stabilizer $\Gamma_{\tilde{x}}$. Then it is not difficult to prove that $\tilde{x}$ has a neighborhood $U_{\tilde{x}}$ which is invariant under $\Gamma_{\tilde{x}}$ and that for all $\tilde{y} \in U_{\tilde{x}}$ the stabilizer $\Gamma_{\tilde{y}} \subset \Gamma_{\tilde{x}}$. This gives us a diagram

$$\begin{array}{ccc} U_{\tilde{x}} & \longrightarrow & \Gamma_{\tilde{x}}\backslash U_{\tilde{x}} = U_x \\ \Big\downarrow & & \Big\downarrow \\ X & \xrightarrow{\pi} & \Gamma\backslash X \end{array}$$

i.e. the point $x \in \Gamma\backslash X$ has a neighborhood which is the quotient of a neighborhood $U_{\tilde{x}}$ by a finite group.

In this case the quotient space $\Gamma\backslash X$ may have singularities. Such spaces are called orbifolds. They have a natural stratification. Any point x defines a Γ conjugacy class $[\Gamma_{\tilde{x}}]$ of finite subgroups $\Gamma_{\tilde{x}} \subset \Gamma$. On the other hand a conjugacy class $[c]$ of finite subgroups $H \subset \Gamma$ defines the (non empty) subset (stratum) $\Gamma\backslash X([c])$ of those points $x \in \Gamma\backslash X$ for which $\Gamma_{\tilde{x}} \in [c]$.

These strata are easy to describe. We observe that for any finite $H \subset \Gamma$ the fixed point set X^H intersected with a connected component of X is contractible.

Let $x_0 \in X^H$ be a point with $\Gamma_{x_0} = H$. Then any other point $x \in X^H$ is of the form $x = gx_0$ with $g \in G(\mathbb{R})$. This implies that $g \in N(H)(\mathbb{R})$, where $N(H)$ is the normaliser of H, it is an algebraic subgroup. Then $N(H)(\mathbb{R}) \cap K = K^H$ is compact subgroup, put $\Gamma^H = \Gamma \cap N(H)(\mathbb{R})$, and we get an embedding

$$\Gamma^H \backslash X^H \hookrightarrow \Gamma \backslash X.$$

This space contains the open subset $(\Gamma^H \backslash X^H)^{(0)}$ of those x where $H \in [\Gamma_{\tilde{x}}]$ and this is in fact the stratum attached to the conjugacy class of H.

We have an ordering on the set of conjugacy classes, we have $[c_1] \leq [c_2]$ if for any $H_1 \in [c_1]$ there exists a subgroup $H_2 \in [c_2]$ such that $H_1 \subset H_2$. These strata are not closed, the closure $\overline{\Gamma \backslash X([c])}$ is the union of lower dimensional strata.

If we start investigating the stratification above we immediately hit upon number theoretic problems.Let us pick a prime p and we consider the group $\Gamma = \mathrm{Sl}_{p-1}[\mathbb{Z}]$ and the ring of p-th roots of unity $\mathbb{Z}[\zeta_p]$ as a $\mathbb{Z}$-module is free of rank $p-1$ and hence we get an element

$$\zeta_p \in \mathrm{Sl}(\mathbb{Z}[\zeta_p]) = \mathrm{Sl}_{p-1}(\mathbb{Z})$$

and hence a cyclic subgroup of order p. But clearly we have many conjugacy classes of elements of order p in Γ because any ideal $\mathfrak{a}$ is a free $\mathbb{Z}$-module. If we want to understand the conjugacy classes of elements of order p or the conjugacy classes of cyclic subgroups of order p in $\mathrm{Sl}_{p-1}(\mathbb{Z})$ we need to understand the ideal class group.

In the next section we will discuss two simple cases.

These quotient spaces $\Gamma \backslash X$ attract the attention of various different kinds of mathematicians. They provide interesting examples of Riemannian manifolds and they are intensively studied from that point of view. On the other hand number theoretic data enter into their construction. Hence any insight into the structure of these spaces contains number theoretic information.

It is not difficult to see that any arithmetic group Γ contains a normal congruence subgroup Γ' which does not have torsion. This can be deduced easily from the exercise .... at the end of this section. Hence we see that $\Gamma' \backslash X$ is a Riemannian manifold which is a finite cover of $\Gamma \backslash X$ with covering group Γ/Γ'.

The following general theorem is due to Borel and Harish-Chandra:

The quotient $\Gamma \backslash X$ always has finite volume with respect to the Riemannian metric. The quotient space $\Gamma \backslash X$ is compact if and only if the group $G/\mathbb{Q}$ is anisotropic.

We will give some further explanation below.

Low dimensional examples

We consider the action of the group $\Gamma = \mathrm{Sl}_2(\mathbb{Z}) \subset \mathrm{Sl}_2(\mathbb{R})$ on the upper half plane

$$X = \mathbb{H} = \{z \mid \Im(z) = y > 0\} = \mathrm{Sl}_2(\mathbb{R})/SO(2).$$

As we explained in .... we may consider the point $z = x+iy$ as a positive definite euclidian metric on $\mathbb{R}^2$ up to a positive scalar. We saw already that this metric can be interpreted as the metric on $\mathbb{C}$ induced on the lattice $\Omega = \langle 1, z\rangle$. The action of $\mathrm{Sl}_2(\mathbb{Z})$ on the upper half plane corresponds to changing the basis $1, z$ of Ω into another basis and then normalizing the first vector of the new basis to length equal one.

This means that under the action of $\mathrm{Sl}_2(\mathbb{Z})$ we may achieve that the first vector 1 in the lattice is of shortest length. In other words $\Omega = \langle 1, z\rangle$ where now $|z| \geq 1$.

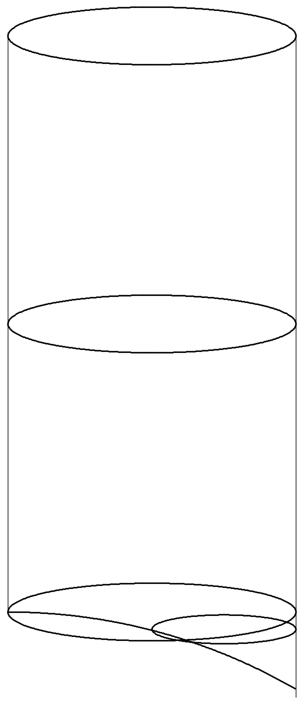
Since we can change the basis by $1 \to 1$ and $z \to z+n$. We still have $|z+n| \geq 1$. Hence see that this condition implies that we can move z by these translation into the strip $-1/2 \leq \Re(z) \leq 1/2$ and since 1 is still the shortest vector we end up in the classical fundamental domain:

$$\mathcal{F} = \{z \mid -1/2 \leq \Re(z) \leq 1/2, |z| \geq 1\}$$

Two points $z_1, z_2 \in \mathcal{F}$ are inequivalent under the action of $\mathrm{Sl}_2(\mathbb{Z})$ unless they differ by a translation. i.e.

$$z_1 = -\frac{1}{2} + it \ , \ z_2 = z_1 + 1 = \frac{1}{2} + it,$$

or we have $|z_1| = 1$ and $z_2 = -\frac{1}{z_1}$. Hence the quotient $\mathrm{Sl}_2(\mathbb{Z})\backslash\mathbb{H}$ is given by the following picture



It turns out that this quotient is actually a Riemann surface, i.e. the finite stabilizers at i and ρ do not produce singularities. As a Riemann surface the quotient is the complex plane or better the projective line $\mathbb{P}^1(\mathbb{C})$ minus the point at infinity.

It is clear that the points i and $\rho = +\frac{1}{2} + \frac{1}{2}\sqrt{-3}$ in the upper half plane are the only points with non-trivial stabilizer up to conjugation by an element $\gamma \in \mathrm{Sl}_2(\mathbb{Z})$. Actually the stabilizers are given by

$$\Gamma_i = \left\{ \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \right\} \quad , \quad \Gamma_\rho = \left\{ \begin{pmatrix} -1 & 1 \\ -1 & 0 \end{pmatrix} \right\}.$$

We denote the matrices

$$S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \ ; \ R = \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix}.$$

The second example is given by the group $\Gamma = \mathrm{Sl}_2(\mathbb{Z}[i]) \subset \mathrm{Sl}_2(\mathbb{C}) = G_\infty$ (see ....). Here we should remember that the choice of $G_\infty = \mathrm{Sl}_2(\mathbb{C})$ allows a whole series of arithmetic groups. For any imaginary quadratic extension $K = \mathbb{Q}(\sqrt{-d})$ with $\mathcal{O}_K$ as its ring of integers we may embed K into $\mathbb{C}$ and get

$$\mathrm{Sl}_2(\mathcal{O}_K) = \Gamma \subset G_\infty.$$

If the number d becomes larger then the structure of the group Γ becomes more and more complicated. We discuss only the simplest case.

We will construct a fundamental domain for the action of Γ on the three-dimensional hyperbolic space $\mathbb{H}_3 = \mathbb{C} \times \mathbb{R}_{>0}$.

We identify $\mathbb{H}_3$ with the space of positive definite hermitian matrices

$$X = \{A \in M_2(\mathbb{C}) \mid A =^t \overline{A}, A > 0, \det(A) = 1\}.$$

We consider the lattice

$$\Omega = \mathbb{Z}[i] \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \mathbb{Z}[i] \cdot \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

in $\mathbb{C}^2$ and view A as a hermitian metric on $\mathbb{C}^2$ where $\mathbb{C}/\Omega$ has volume 1. Let $e_1' = \binom{\alpha}{\beta}$ be a vector of shortest length. We can find a second vector $e_2' = \binom{\gamma}{\delta}$ so that $\det \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} = 1$. This argument is only valid because $\mathbb{Z}[i]$ is a principal ideal domain. We consider the vectors $e_2' + \nu e_1'$ where $\nu \in \mathbb{Z}[i]$. We have

$$\langle e_2' + \nu e_1', e_2' + \nu e_1' \rangle_A = \langle e_2' + \nu e : 1' \rangle_A + \nu \langle e_1', e_2' \rangle_A + \overline{\nu} \langle e_2', e_1' \rangle_a + \nu\overline{\nu} \langle e_1', e_1' \rangle_A.$$

Since we have the the euclidean algorithm in $\mathbb{Z}[i]$ we can choose ν such that

$$-\frac{1}{2}\langle e_1', e_1' \rangle \leq \mathrm{Re}\langle e_1', e_2' \rangle_A, \Im\langle e_1', e_2' \rangle_A \leq \frac{1}{2}\langle e_1', e_1' \rangle_A.$$

If we translate this to the action of $\mathrm{Sl}_2(\mathbb{Z}[i])$ on $\mathbb{H}_3$ then we find that every point $x = (z; \zeta) \in \mathbb{H}_3$ is equivalent to a point in the domain

$$\tilde{F} = \{(z, \zeta) \mid -\frac{1}{2} \leq \mathrm{Re}(z), \Im(z) \leq \frac{1}{2}; z\overline{z} + \zeta^2 \geq 1\}.$$

Since we have still the action of the matrix $\begin{pmatrix} i & 0 \\ 0 & -1 \end{pmatrix}$ we even find a smaller fundamental domain

$$F = \{(z, \zeta) \mid -\frac{1}{2} \leq \mathrm{Re}(z), \Im(z) \leq \frac{1}{2}; z\overline{z} + \zeta^2 \geq 1 \text{ and } \mathrm{Re}(z) + \Im(z) \geq 0\}.$$

I want to discuss also the extension of our considerations to the case of the reductive group $\mathrm{Gl}_2(\mathbb{C})$. In such a case we have to enlarge the maximal compact subgroup. In this case the group $\tilde{K} = \mathrm{Sl}_1(2) \cdot \mathbb{C}^* = K \cdot \mathbb{C}^*$ is a good choice where $\mathbb{C}^*$ is the centre of $\mathrm{Gl}_2(\mathbb{C})$. Then we get

$$\mathbb{H}_3 = \mathrm{Sl}_2(\mathbb{C})/K = \mathrm{Gl}_2(\mathbb{C})/\tilde{K}$$

i.e. we have still the same symmetric space. But the group $\tilde{\Gamma} = \mathrm{Gl}_2(\mathbb{Z}[i])$ is still larger. We have an exact sequence

$$1 \to \Gamma \to \tilde{\Gamma} \to \{i^\nu\} \to 1.$$

The centre $Z_{\tilde{\Gamma}}$ of $\tilde{\Gamma}$ is given by the matrices $\left\{\begin{pmatrix} i^v & 0 \\ 0 & i^v \end{pmatrix}\right\}$. The centre Z_Γ has index 2 in $Z_{\tilde{\Gamma}}$. Since the centre acts trivially on the symmetric space, hence the above fundamental domain will be "cut into two halfes" by the action of $\tilde{\Gamma}$. the matrices $\begin{pmatrix} i^v & 0 \\ 0 & 1 \end{pmatrix}$ induce rotation of $\nu \cdot 90°$ around the axis $z = 0$ and therefore it becomes clear that the region

$$F_0 = \{(z, \zeta) \mid 0 \leq \Im(z), \mathrm{Re}(z) \leq \frac{1}{2}, z\overline{z} + \zeta^2 \geq 1\}$$

is a fundamental domain for $\tilde{\Gamma}$.

The translations $z \to z + 1$ and $z \to z + i$ identify the opposite faces of F. This induces an identification on F_0, namely

$$\left(\frac{1}{2} + iy, \zeta\right) \longrightarrow \left(-\frac{1}{2} + iy, \zeta\right) \longrightarrow \left(y + \frac{i}{2}, \zeta\right).$$

On the bottom of the domain F_0, namely

$$F_0(1) = \{(z, \zeta) \in F_0 \mid z\overline{z} + \zeta^2 = 1\}$$

we have the further identification

$$(z, \zeta) \longrightarrow (i\overline{z}, \zeta).$$

Hence we see that the quotient space $\tilde{\Gamma}\backslash\mathbb{H}_3$ is given by the following figure.

Insertpicture

I want to discuss the fixed points and the stabilizers of the fixed points of $\tilde{\Gamma}$. Before I can do that, I need some simple facts concerning the structure of Gl_2.

The group $\mathrm{Gl}_2(K)$ acts upon the projective line $\mathbb{P}^1(K) = (K^2 \setminus \{0\})/K^*$. We write

$$\mathbb{P}^1(K) = (K) \cup \{\infty\}\ ;\ K(xe_1 + e_2) = x, Ke_1 = \infty.$$

It is quite clear that the action of $g = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \in \mathrm{Gl}_2(K)$ is given by

$$gx = \frac{\alpha x + \beta}{\gamma x + \delta}.$$

The action of $\mathrm{Gl}_2(K)$ on $\mathbb{P}^1(K)$ is transitive. For a point $x \in \mathbb{P}^1(K)$ the stabilizer B_x is clearly a linear subgroup of Gl_2/K. If $x = \infty$, then this stabilizer is the subgroup

$$B_\infty = \left\{\begin{pmatrix} a & u \\ 0 & b \end{pmatrix}\right\},$$

and for $x = 0$ we get

$$B_0 = \left\{ \begin{pmatrix} a & 0 \\ u & b \end{pmatrix} \right\}.$$

It is clear that these subgroups B_x are conjugate under the action of $\mathrm{Gl}_2(K)$. They are in fact maximal solbable subgroups of Gl_2.

If we have two different points $x_1, x_2 \in \mathbb{P}^1(K)$, then this corresponds to a choice of a basis where the basis vectors are only determined up to scalars. Then the intersection of the two groups $B_{x_1} \cap B_{x_2}$ is a so-called maximal torus. If we choose $x_1 = Ke_1$, $x_2 = Ke_2$, then

$$B_{x_1} \cap B_{x_2} = \left\{ \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix} \right\}.$$

Any other maximal torus of the form B_{x_1}, B_2 is conjugate to T_0 under $\mathrm{Gl}_2(K)$.

Now we assume $K = \mathbb{C}$. We compactify the three dimensional hyperbolic space by adding $\mathbb{P}^1(\mathbb{C})$ at infinity, i.e.

$$\mathbb{H}_3 \hookrightarrow \overline{\mathbb{H}}_3 = \mathbb{H}_3 \cup \mathbb{P}^1(\mathbb{C}) = \mathbb{C} \times \mathbb{R}_{\geq 0} \cup \{\infty\}.$$

(The reader should verify that there is a natural topology on $\overline{\mathbb{H}}_3$ for which the space is compact and for which $\mathrm{Gl}_2(\mathbb{C})$ acts continuously.)

Now let us assume that $a \in \mathrm{Gl}_2(\mathbb{C})$ is an element which has a fixed point on $\mathbb{H}_3$ and which is not central. Since it lies in a maximal compact subgroup times $\mathbb{C}^x$ we see that this element a can be diagonalized

$$a \longrightarrow g_0 \; a \; g_0^{-1} = \begin{pmatrix} \alpha & 0 \\ 0 & \beta \end{pmatrix} = a'$$

with $\alpha \neq \beta$ and $|\alpha/\beta| = 1$.

Then it is clear that the fixed point set for a' is the line

$$\mathrm{Fix}\;(a') = \{(0, \zeta) \mid \zeta \in \mathbb{R}_{>0}\},$$

i.e. we do not get an isolated fixed point but a full fixed line.

The element a' has the two fixed points $\infty, 0$ in $\mathbb{P}^1(\mathbb{C})$, and hence ist defines the torus $T_0(\mathbb{C})$. Then it is clear that

$$\mathrm{Fix}(a') = \{(0, \zeta) \mid \zeta > 0\} = T_0(\mathbb{C}) \cdot (0, 1)$$

i.e. the fixed point set is an orbit under the action of $T_0(\mathbb{C})$.

Fixed point sets and stabilizers for $\mathrm{Gl}_2(\mathbb{Z}[i]) = \tilde{\Gamma}$

If we want to describe the stabilizers up to conjugation, we can focus our attention on F_0.

If we have an element $\gamma \in \tilde{\Gamma}$, γ not central and if we assume that γ has fixed points on $\mathbb{H}_3$, then we know that γ defines a torus $T_\gamma = \mathrm{centralizer}_{\mathrm{Gl}_2}(\gamma) =$ stabilizer of $x_\gamma, x_{\gamma'} \in \mathbb{P}^1(\mathbb{C})$. This torus is defined over $\mathbb{Q}(i)$, but it is not necessarily diagonalizable over $\mathbb{Q}(i)$, it may be that the coordinates of $x_\gamma, x_{\gamma'}$ lie in a quadratic extension of $F/\mathbb{Q}(i)$. This is the quadratic extension defined by the eigenvalues of γ.

We look at the edges of the fundamental domain F_0. We saw that they consist of connected pieces of the straight lines

$$G_1 = \{(z,\zeta) \mid z = 0\}, G_2 = \{(z,\zeta) \mid z = \frac{1}{2}\}, G_3 = \{(z,\zeta) \mid z = \frac{1+i}{2}\},$$

and the circles (these circles are euclidean circles and geodesics for the hyperbolic metric)

$$D_1 = \{(z,\zeta) \mid z\overline{z} + \zeta^2 = 1, \Im(z) = \mathrm{Re}(z)\}, D_2 = \{(z,\zeta) \mid z\overline{z} + \zeta^2 = 1, \Im(z) = 0\},$$

$$D_3 = \{(z,\zeta) \mid z\overline{z} + \zeta^2 = 1, \mathrm{Re}(z) = \frac{1}{2}\}.$$

The pair of points $(\infty, (z_0, 0)) \in \mathbb{P}^1(\mathbb{C}) \times \mathbb{P}^1(\mathbb{C})$ has as its stabilizer

$$T_{z_0}(\mathbb{C}) = \begin{pmatrix} 1 & z_0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \alpha & 0 \\ 0 & \beta \end{pmatrix} \begin{pmatrix} 1 & -z_0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} \alpha & z_0(\beta - \alpha) \\ 0 & \beta \end{pmatrix},$$

the straight line $\{(z_0, \zeta) \mid \zeta > 0\}$ is an orbit u nder $T_{z_0}(\mathbb{C})$ and it consists of fixed points for

$$T_{z_0}(\mathbb{C})(1) = \left\{ \begin{pmatrix} \alpha & z_0(\beta - \alpha) \\ 0 & \beta \end{pmatrix} \,\middle|\, \alpha/\beta \in S^1 \right\}.$$

We can easily compute the pointwise stabilizer of G_1, G_2, G_3 in $\tilde{\Gamma}$. They are

$$\begin{aligned}
\tilde{\Gamma}_{G_1} &= \left\{ \begin{pmatrix} i^\nu & 0 \\ 0 & i^\mu \end{pmatrix} \right\} = \left\{ \begin{pmatrix} i^\nu & 0 \\ 0 & i \end{pmatrix} \right\} \cdot z_{\tilde{\Gamma}} \\
\Gamma_{\tilde{G}_2} &= \left\{ \begin{pmatrix} i^\nu & \frac{1-i^\nu}{2} \\ 0 & 1 \end{pmatrix} \,\middle|\, \frac{1-i^\nu}{2} \in \mathbb{Z}[i] \right\} \cdot Z_{\tilde{\Gamma}} = \left\{ \begin{pmatrix} \pm 1 & \frac{1 \pm 1}{2} \\ 0 & 1 \end{pmatrix} \right\} \cdot Z_{\tilde{\Gamma}} \\
\Gamma_{\tilde{G}_3} &= \left\{ \begin{pmatrix} i^\nu & \frac{(1-i^\nu)(1+i)}{2} \\ 0 & 1 \end{pmatrix} \right\} \cdot Z_{\tilde{\Gamma}},
\end{aligned}$$

where in the last case we have to take into account that $\frac{(1-i^\nu)(1+i)}{2} \in \mathbb{Z}[i]$ for all ν.

Hence modulo the centre $Z_{\tilde{\Gamma}}$ these stabilizers are cyclic groups of order $4, 2, 4$.

The arcs D_i are also pointwise fixed under the action of certain cyclic groups, namely

$$\begin{aligned}
D_1 =& \mathrm{Fix}\left(\begin{pmatrix} 0 & i \\ 1 & 0 \end{pmatrix} \right) \\
D_2 =& \mathrm{Fix}\left(\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \right) \\
D_3 =& \mathrm{Fix}\left(\begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix} \right),
\end{aligned}$$

and we check easily that these arcs are geodesics joining the following points in the boundary

$$\begin{aligned}
&D_1 \text{ runs from } \sqrt{i} \text{ to } -\sqrt{i} \\
&D_2 \text{ runs from } i \text{ to } -i \\
&D_3 \text{ runs from } e = e^{\frac{1\pi i}{6}} = e^{\frac{\pi i}{3}} \text{ to } \overline{\rho}.
\end{aligned}$$

The corresponding tori are

$$\begin{aligned} T_1 =& \mathrm{Stab}(-1,1) = \left\{ \begin{pmatrix} \alpha & i\beta \\ \beta & \alpha \end{pmatrix} \right\} \\ T_2 =& \mathrm{Stab}(-\sqrt{i},\sqrt{i}) = \left\{ \begin{pmatrix} \alpha & \beta \\ \beta & \alpha \end{pmatrix} \right\} \\ T_3 =& \mathrm{Stab}(\rho,\overline{\rho}) = \left\{ \begin{pmatrix} \delta-\beta & \beta \\ -\beta & \delta \end{pmatrix} \right\}. \end{aligned}$$

The torus T_2 splits over $\mathbb{Q}(i)$, the other two tori split over an quadratic extension of $\mathbb{Q}(i)$.

Now it is not difficult anymore to describe the finite stabilizers and the corresponding fixed point sets. If $x \in \mathbb{H}_3$ for which the stabilizer is bigger than $Z_{\tilde{\Gamma}}$, then we can conjugate x into F_0. It is very easy to see that x cannot lie in the interior of F_0 because then we would get an identification of two points nearby x and hence still in F_0 under $\tilde{\Gamma}$.

If x is on one of the lines D_1, D_2, D_3 or on one of the arcs G_1, G_2, G_3 but not on the intersection of two of them, then the stabilizer Γ_x is equal to $Z_{\tilde{\Gamma}}$ times the cyclic group we attached to the line or the arc earlier. Finally we are left with the three special points

$$\begin{aligned} x_{12} =& D_1 \cap D_2 \cap G_1 = \{(0,1)\} \\ x_{13} =& D_1 \cap D_3 \cap G_3 = \left\{ \left(\frac{1+i}{2}, \frac{\sqrt{2}}{2} \right) \right\} \\ x_{23} =& D_2 \cap D_3 \cap G_2 = \left\{ \left(\frac{1}{2}, \frac{\sqrt{3}}{2} \right) \right\}. \end{aligned}$$

In this case it is clear that the stabilizers are given by

$$\begin{aligned} \tilde{\Gamma}_{x_{12}} =& \langle \begin{pmatrix} 0 & i \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} i & 0 \\ 0 & 1 \end{pmatrix} \rangle = D_4 \\ \tilde{\Gamma}_{x_{13}} =& \langle \begin{pmatrix} 0 & i \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} i & 1 \\ 0 & 1 \end{pmatrix} \rangle = S_4 \\ \tilde{\Gamma}_{x_{23}} =& \langle \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix} \rangle = S_3. \end{aligned}$$

1.2.2 Compactification of $\Gamma\backslash X$

Our two special low dimensional examples show clearly that the quotient spaces $\Gamma\backslash X$ are not compact in general. There exist various constructions to compactify them.

If, for instance, $\Gamma \subset \mathrm{Sl}_2(\mathbb{Z})$ is a subgroup of finite index, then the quotient $\Gamma\backslash\mathbb{H}$ is a Riemann surface. It can be embedded into a compact Riemann surface by adding a finite number of points. this is a special case of a more general theorem of Satake and Baily-Borel: If the symmetric space X is actually hermitian symmetric (this means it has a complex structure) then we have the structure of a quasi-projective variety on $\Gamma\backslash X$. This is the so-called Baily-Borel compactification. It exists only under special circumstances.

I will discuss the process of compactification in some more detail for our special low dimensional examples.

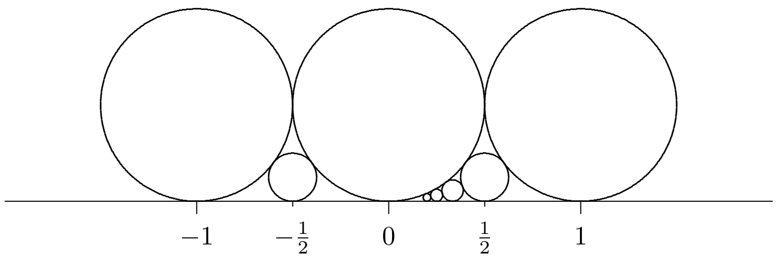
Compactification of $\mathrm{Sl}_2(\mathbb{Z})\backslash\mathbb{H}$ by adding points

Let $\Gamma \subset \mathrm{Sl}_2(\mathbb{Z})$ be any subgroup of finite index. The group Γ acts on the rational projective line $\mathbb{P}^1(\mathbb{Q})$. We add it to the upper half plane and form

$$\overline{\mathbb{H}} = \mathbb{H} \cup \mathbb{P}^1(\mathbb{Q}),$$

and we extend the action of Γ to this space. Since the full group $\mathrm{Sl}_2(\mathbb{Z})$ acts transitively on $\mathbb{P}^1(\mathbb{Q})$ we find that Γ has only finitely many orbits on $\mathbb{P}^1(\mathbb{Q})$.

Now we introduce a topology on $\overline{\mathbb{H}}$. We defined a system of neighborhoods of points $\frac{p}{q} = r \in \mathbb{P}^1(\mathbb{Q})$. We define the Farey circles $S\left(c, \frac{p}{q}\right)$ which touch the real axis in the point $r = p/q$ $(p,q) = 1$ and have the radius $\frac{c}{2q^2}$. For $c = 1$ we get the picture



Let us denote by $D\left(c, \frac{p}{q}\right) = \cup_{c':0<c'\leq c} S\left(c', \frac{p}{q}\right)$ the Farey disks. For $c \to 0$ these Farey disks $D\left(c, \frac{p}{q}\right)$ define a system of neighborhoods of the point $r = p/q$. The Farey disks at $\infty \in \mathbb{P}^1(\mathbb{Q})$ are given by the regions

$$D(T, \infty) = \{z \mid \Im(z) \geq T\}.$$

It is easy to check that an element $\gamma \in \mathrm{Sl}_2(\mathbb{Z})$ which sends $\infty \in \mathbb{P}^1(\mathbb{Q})$ into the point $r = \frac{p}{q}$ sends $D(T, \infty)$ to $D\left(\frac{1}{T}, \frac{p}{q}\right)$. These Farey disks $D(c, r)$ do not meet provided we take $c < 1$. The considerations in 1.6.1 imply that the complement of the union of Farey disks is relatively compact modulo Γ, and since Γ has finitely many orbits on $\mathbb{P}^1(\mathbb{Q})$, we see easily that

$$Y_\Gamma = \Gamma\backslash\overline{\mathbb{H}}$$

is compact (which means of course also Hausdorff).

It is essential that the set of Farey circles $D(c, r)$ and $D\left(\frac{1}{c}, \infty\right)$ is invariant under the action of Γ on the one hand and decomposes into several connected components (which are labeled by the point $r \in \mathbb{P}^1(\mathbb{Q})$) on the other hand. Hence

$$\Gamma\backslash\bigcup_r D(c, r) = \bigcup \Gamma_{r_i}\backslash D(c, r_i)$$

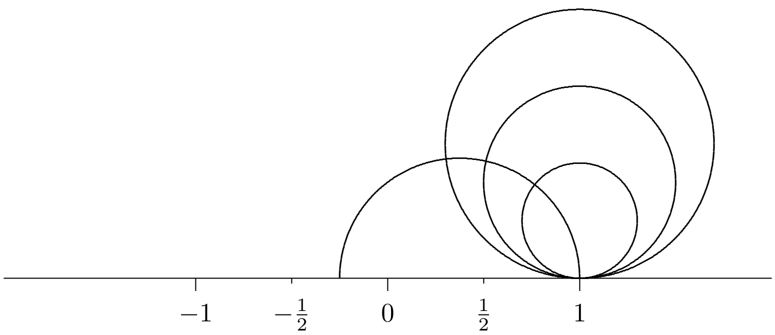
where r_i is a set of representatives for the action of Γ on $\mathbb{P}^1(\mathbb{Q})$ and where Γ_{r_i} is the stabilizer of r_i in Γ.

It is now clear that $\Gamma_{r_i}\backslash D(c, r_i)$ is holomorphically equivalent to a punctured disc and hence the above compactification is obtained by filling the point into this punctured disc and this makes it clear that Y_Γ is a Riemann surface.

$\boxed{\text{BSC}}$

The Borel-Serre compactification of $\mathbf{Sl}_2(\mathbb{Z})\backslash\mathbb{H}$

There is another construction of a compactification. We look at the disks $D(c, r)$ and divide them by the action of Γ_r. For any point $y \in S(c', r) - \{r\}$ there exists a unique geodesic joining r and y, passing orthogonally through $S(c', r)$ and hitting the projective line in another point y_∞ ($= -1/4$ in the picture below)



If $r = \infty$, then this system of geodesics is given by the vertical lines $\{y \cdot I + x \mid x \in \mathbb{R}\}$.. This allows us to write the set

$$D(c, r) - \{r\} = X_{\infty,r} \times [c, 0)$$

where $X_{\infty,r} = \mathbb{P}^1(\mathbb{R}) - \{r\}$. The stabilizer Γ_r acts $D(c, r)$ and on the right hand side of the identification it acts on the first factor, the quotient $\Gamma_r\backslash X_{\infty,r}$ is a circle. Hence we can compactify the quotient

$$\Gamma_r\backslash D(c, r) - \{r\} \hookrightarrow \Gamma_r\backslash X_{\infty,r} \times [c, 0].$$

This gives us a second way to compactify $\Gamma\backslash\mathbb{H}$, we apply this process to a finite set of representatives of $\mathbb{P}^1(\mathbb{Q}) \mod \Gamma$.

There is a slightly different way of looking at this. We may form the union

$$\mathbb{H} \cup \bigcup_r X_{\infty,r} = \tilde{\mathbb{H}}$$

and topologize it in such a way that

$$D(c, r) = X_{\infty,r} \times [c, 0) \subset X_{\infty,r} \times [c, 0]$$

is a local homeomorphism. Then we see that the compactification above is just the quotient

$$\Gamma\backslash\tilde{\mathbb{H}}$$

and the boundary is simply

$$\partial(\Gamma\backslash\bar{\mathbb{H}}) = \Gamma\backslash \bigcup_{r\in\mathbb{P}^1(\mathbb{Q}} X_{\infty,r}.$$

This compactification is called the Borel-Serre compactification. Its relation to the Baily-Borel is such that the latter is obtained by the former by collapsing the circles at infinity to a point.

It is quite clear that a similar construction applies to the action of a group $\Gamma \subset \mathrm{Sl}_2(\mathbb{Z}[i])$ on the three-dimensional hyperbolic space. The Farey circles will be substituted by spheres $S(c,\alpha)$ which touch the complex plane $\{(z,0) \mid z \in \mathbb{C}\} \subset \overline{\mathbb{H}}_3$ in the point $(\alpha,0), \alpha \in \mathbb{P}^1(\mathbb{Q}(i))$ and for $\alpha = \infty$ the Farey sphere is the horizontal plane $S(\infty,\zeta_0) = \{(z,\zeta_0) \mid z \in \mathbb{C})$. An element $\gamma \in \Gamma$ which maps $(0,\infty)$ to α maps $S(\infty,\zeta_0)$ to $S(c,\alpha)$, where $c = 1/\zeta_0$. For a given α we may identify the different spheres if we vary c and for any point $\alpha \in \mathbb{P}^1(\mathbb{Q}(i))$ we define $X_{\infty,\alpha} = \mathbb{P}^1(\mathbb{C}) \setminus \{\alpha\}$. Again we can identify

$$D(c,\alpha) \setminus \{\alpha\} = X_{\infty,\alpha} \times (0,c] \subset \overline{D(c,\alpha) \setminus \{\alpha\}} = \partial(\Gamma\backslash\mathbb{H}) = X_{\infty,\alpha} \times [0,c]$$

The stabilizer Γ_α acts on $D(c,\alpha) \setminus \{\alpha\}$ and again this yields an action on the first factor. If we choose $\alpha = \infty$ then

$$\Gamma_\infty = \{\begin{pmatrix} \zeta & a \\ 0 & \zeta^{-1} \end{pmatrix} |\zeta \text{ root of unity}, a \in M_\infty\}$$

where M_∞ is a free rank 2 module in $\mathbb{Z}[i]$. If ζ does not assume the value i then $\Gamma_\infty\backslash X_{\infty,\infty}$ is a two-dimensional torus, a product of two circles. If ζ assumes the value i then $\Gamma_\infty\backslash X_{\infty,\infty}$ is a two dimensional sphere. If course we get the same result for an arbitrary α.

Then we get an action of the group Γ on $\tilde{\mathbb{H}}_3 = \mathbb{H}_3 \cup \bigcup_{\alpha\in\mathbb{P}^1(K)} \overline{D(c,\alpha) \setminus \{\alpha\}}$ and the quotient is compact.

The the set of orbits of Γ on $\mathbb{P}^1(\mathbb{Q}(i))$ is finite, these orbits are called the cusps.

The Borel-Serre compactification, reduction theory of arithmetic groups

The Borel-Serre compactification works in complete generality for any semi-simple or reductive group $G/\mathbb{Q}$. To explain it, we need the notion of a parabolic subgroup of $G/\mathbb{Q}$.

A subgroup $P/\mathbb{Q} \hookrightarrow G/\mathbb{Q}$ is parabolic if the quotient variety in the sense of algebraic geometry is a projective variety. We mentioned already earlier that for the group $\mathrm{Gl}_2/\mathbb{Q}$ we have an action of Gl_2 on the projective line $\mathbb{P}^1$ and the stabilizers B_x of the points $x \in \mathbb{P}^1(\mathbb{Q})$ are the so-called Borel subgroups of $\mathrm{Gl}_2/\mathbb{Q}$. They are maximal solvable subgroups and

$$\mathrm{Gl}_2/B_x = \mathbb{P}^1,$$

hence they are also parabolic.

More generally we get parabolic subgroups of $\mathrm{Gl}_n/\mathbb{Q}$, if we choose a flag on the vector space $V = \mathbb{Q}^n = \mathbb{Q}e_1 \oplus \cdots \oplus \mathbb{Q}e_n$. This is an increasing sequence of subspaces

$$\mathcal{F} : (0) = \{(0)\} = V_0 \subset V_1 \subset V_2 \ldots V_k = V.$$

The stabilizer P of such a flag is always a parabolic subgroup; the quotient space

$$G/P = \text{Variety of all flags of the given type},$$

where the type of the flag is the sequence of the dimensions $n_i = \dim V_i$.

These flag varieties (the Grassmannians) are smooth projective schemes over $\mathrm{Spec}(\mathbb{Z})$ and this implies that any flag $\mathcal{F}$ is induced by a flag

$$\mathcal{F}_{\mathbb{Z}} : (0) = \{(0)\} = L_0 \subset L_1 \subset L_2 \subset \ldots \subset L_k = L = \mathbb{Z}^n \tag{1.15}$$

where $L_i = V_i \cap L$, and of course $L_i \otimes \mathbb{Q} = V_i$.This is the elementary fact which will be used later.

If our group $G/\mathbb{Q}$ is the orthogonal group of a quadratic form

$$f(x_1, \ldots, x_n) = \sum_{i=1}^{n} a_i x_i^2$$

with $a_i \in K^*$. Then we have to replace the flags by sequences of subspaces

$$\mathcal{F} : 0 \subset W_1 \subset W_2 \ldots \qquad\qquad \subset W_2^{\perp} \subset W_1^{\perp} \subset V,$$

where the W_i are isotropic spaces for the form f, i.e. $f \mid W_i \equiv 0$, and where the $W_i^{\perp}$ are the orthogonal complements of the subspaces. Again the stabilizers of these flags are the parabolic subgroups defined over $\mathbb{Q}$.

Especially, if the form f is anisotropic over $\mathbb{Q}$, i.e. there is no non-zero vector $\underline{x} \in K^n$ with $f(\underline{x}) = 0$, then the group $G/\mathbb{Q}$ does not have any parabolic subgroup over $\mathbb{Q}$. This equivalent to the fact that $G(\mathbb{Q})$ does not have unipotent elements.

These parabolic subgroups always have a unipotent radical U_P which is always the subgroup which acts trivially on the successive quotients of the flag. The unipotent radical is a normal subgroup, the quotient $P/U_P = M$ is a reductive group again, it is called the Levi-quotient of P.

We stick to the group $\mathrm{Gl}_n/\mathbb{Q}$. It contains the standard maximal torus whose R valued points are

$$T_0(R) = \{ \begin{pmatrix} t_1 & 0 & \ldots & 0 \\ 0 & t_2 & \ldots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & t_n \end{pmatrix} \quad \mid \quad t_i \in R^{\times}, \prod t_i = 1\} \tag{1.16}$$

It is a subgroup of the Borel subgroup (maximal solvable subgroup or minimal parabolic subgroup)

$$B_0(R) = \{ \begin{pmatrix} t_1 & u_{1,2} & \dots & u_{1,n} \\ 0 & t_2 & \dots & u_{2,n} \\ 0 & 0 & \ddots & u_{n-1,n} \\ 0 & 0 & 0 & t_n \end{pmatrix} \quad | \quad t_i \in R^\times, \prod t_i = 1\} \tag{1.17}$$

and its unipotent radical U_0 consists of those $b \in B_0$ where all the $t_i = 1$. This unipotent radical contains the one dimensional root subgroups

$$U_{i,j} = \{ \begin{pmatrix} 1 & 0 & \dots & 0 & 0 \\ 0 & 1 & \dots & 0 & 0 \\ 0 & 0 & \ddots & x & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \} \tag{1.18}$$

where $i < j$, these one dimensional subgroups are isomorphic to the one dimensional additive group $\mathbb{G}_a$. They are normalized by the torus, for an element $t \in T(R)$ and $x_{i,j} \in U_{i,j}(R) = R$ we have

$$tx_{i,j}t^{-1} = t_i/t_jx_{i,j}. \tag{1.19}$$

For $i = 1, \dots, n, j = 1, \dots, n, i \neq j$ (resp. $i < J$) characters $\alpha_{i,j}(t) = t_i/t_j$ are called the roots (resp. positive roots) of T_0 in Gl_n. We denote these systems of roots by Δ^{Gl_n} (resp)$\Delta_+^{\mathrm{Gl}_n}$. The one dimensional subgroups $U_{i,j}, i \neq j$ are called the root subgroups. Inside the set of positive roots we have the set of simple roots

$$\pi = \pi^{\mathrm{Gl}_n} = \{\alpha_{1,2}, \dots, \alpha_{i,i+1}, \dots, \alpha_{n-1,n}\} \tag{1.20}$$

We change the notation slightly, for $i = 1, \dots, n-1$ we define $\alpha_i := \alpha_{i,i+1}$ then for $i < j$ we get $\alpha_{i,j} = \alpha_i + \dots \alpha_{j-1}$, and $\pi = \{\alpha_1, \alpha_2, \dots, \alpha_{n-1}\}$

The Borel subgroup B_0 is the stabilizer of the "complete" flag

$$\{0\} \subset \mathbb{Q}e_1 \subset \mathbb{Q}e_1 \oplus \mathbb{Q}e_2 \subset \dots \subset \mathbb{Q}e_1 \oplus \mathbb{Q}e_2 \oplus \dots \oplus \mathbb{Q}e_n, \tag{1.21}$$

the parabolic subgroups $P_0 \supset B_0$ are the stabilizers of "partial" flags

$$\{0\} \subset \mathbb{Q}e_1 \oplus \dots \oplus \mathbb{Q}e_{n_1} \subset \mathbb{Q}e_1 \oplus \dots \oplus \mathbb{Q}e_{n_1} \oplus \mathbb{Q}e_{n_1+1} \oplus \dots \oplus \mathbb{Q}e_{n_1+n_2} \subset \dots \subset \mathbb{Q}^n. \tag{1.22}$$

The parabolic subgroup P_0 also acts on the direct sum of the successive quotients

$$\mathbb{Q}e_1 \oplus \dots \oplus \mathbb{Q}e_{n_1} \oplus \mathbb{Q}e_{n_1+1} \oplus \dots \oplus \mathbb{Q}e_{n_1+n_2} \oplus \dots \tag{1.23}$$

and this yields a homomorphism

$$r_{P_0} : P_0 \to M_0 = \mathrm{Gl}_{n_1} \times \mathrm{Gl}_{n_2} \times \dots \tag{1.24}$$

hence M_0 is the Levi quotient of P_0. By definition the unipotent radical U_{P_0} of P_0 is the kernel of r_0.

A parabolic subgroups $P_0 \supset B_0$ defines a subset

$$\Delta^{P_0} = \{\alpha_{i,j} \in \Delta^{\mathrm{Gl}_n} \mid U_{i,j} \subset P_0\}$$

and the set decomposes int two sets

$$\Delta^{U_{P_0}} = \{\alpha_{i,j} \mid U_{i,j} \subset \Delta^{U_{P_0}}\}, \Delta^{M_0} = \{\alpha_{i,j} \mid U_{i,j}, U_{j,i} \subset \Delta^{P_0}\} \tag{1.25}$$

Intersecting this decomposition with the set π^{Gl_n} yields a disjoint decomposition

$$\pi^{\mathrm{Gl}_n} = \pi^{M_0} \cup \pi^U \tag{1.26}$$

where $\pi^U = \{\alpha_{n_1}, \alpha_{n_1+n_2}, \dots, \}$. In turn any such decomposition of π^{Gl_n} yields a well defined parabolic $P_0 \supset B_0$.

If we choose another maximal split torus T_1 and a Borel subgroup $B_1 \supset T_1$ then this amounts to the choice of a second ordered basis $v_1, v_2, \dots, v_n$ the v_i are given up to a non zero scalar factor. We can find a $g \in \mathrm{Gl}_n(\mathbb{Q})$ which maps $e_1, e_2, \dots, e_n$ to $v_1, v_2, \dots, v_n$, and hence we can conjugate the pair (B_0, T_0) to (B_1, T_1) and hence the parabolic subgroups containing B_0 into the parabolic subgroups containing B_1. The conjugating element g also identifies

$$i_{T_0,B_0,T_1,B_1} : X^*(T_0) \xrightarrow{\sim} X^*(T_1)$$

and this identification does not depend on the choice of the conjugating element g. This allows us to identify the two set of positive simple roots $\pi^{\mathrm{Gl}_n} \subset X^*(T_0)$ and $\pi \subset X^*(T_1)$. Eventually we can speak of the set π of simple roots of Gl_n. Hence we have the fundamental fact

The $Gl_n(\mathbb{Q})$ conjugacy classes of parabolic subgroups $P/\mathbb{Q}$ are in one to one correspondence with the subsets $\pi' \subset \pi$ where π' is the set of those simple roots α_i for which $U_{i,i+1} \subset U_P$, the unipotent radical of P. Then number of elements in π' is called the rank of P, the set $\pi\prime$ is called the type of P.

We will denote the unipotent radical of P by U_P and the the reductive quotient of P by U_P will be denoted by $M_P = P/U_P$. We will write $\pi' = \pi^{U_P} \subset \pi$ and $\pi^{M_P} = \pi \setminus \pi^{U_P}$ is the system of simple roots of M_P.

We formulated this result for $\mathrm{Gl}_n/\mathbb{Q}$ but we can replace $\mathbb{Q}$ by any field k and Gl_n by any reductive group G/k. We have to define the system of relative simple positive roots π^G for any G/k (See [B-T]).

The group G/k itself is also a parabolic subgroup it corresponds to $\pi' = \emptyset$. We decide that we do not like it and hence we consider only proper parabolic subgroups $P \neq G$, i.e. $\pi' \neq \emptyset$. We can define the Grassmann variety $\mathrm{Gr}^{[\pi']}$ of parabolic subgroups of type π. This is a smooth projective variety and $\mathrm{Gr}^{[\pi']}(\mathbb{Q})$ is the set of parabolic subgroups of type π.

There is always a unique minimal conjugacy class it corresponds to $\pi' = \pi^G$. (In our examples this minimal class is given by the maximal flags, i.e. those flags where the dimension of the subspaces increases by one at each step (until we reach a maximal isotropic space in the case of an orthogonal group)). The (proper) maximal parabolic subgroups are those for which $\pi' = \{\alpha_i\}$, i.e. π consist of one element.

We go back to the special case $\mathrm{Gl}_n/\mathbb{Q}$, the following results are true in general but their formulation is just a little bit more involved.

For a maximal parabolic subgroup P of type $\pi' = \{\alpha_i\}$ we consider the module $\mathrm{Hom}(P, \mathbb{G}_m) \otimes \mathbb{Q} \subset X^*(T) \otimes \mathbb{Q}$. Of course it always contains the determinant and

$$\mathrm{Hom}(P, \mathbb{G}_m) \otimes \mathbb{Q} = \mathbb{Q}\gamma_i \oplus \mathbb{Q}\det$$

where γ_i is

$$\gamma_i(t) = (\prod_{\nu=1}^{\nu=i} t_\nu) \det(t)^{-i/n}. \tag{1.27}$$

These γ_i are called the dominant fundamental weights.

If our maximal parabolic subgroup is $P/\mathbb{Q}$ is defined as the stabilizer of a flag $0 \subset W \subset V = \mathbb{Q}^n$, then the unipotent radical is $U = \mathrm{Hom}(V/W, W)$. An element $y \in P(\mathbb{Q})$ induces linear maps $y_W, y_{V/W}$ and hence $\mathrm{Ad}(y)$ on $U = \mathrm{Hom}(V/W, W)$. We get a character $\gamma_P(y) = \det(\mathrm{Ad}(y)) \in \mathrm{Hom}(P, \mathbb{G}_m)$ which is called the sum of the positive roots. An easy computation shows that

$$n\gamma_i = \gamma_P \tag{1.28}$$

We add points at infinity to our symmetric space: We consider the disjoint union $\cup_{\pi \neq \pi_G} \mathrm{Gr}^{[\pi']}(\mathbb{Q})$ and form the space

$$\overline{X} = X \cup \bigcup_{\pi' \neq \emptyset} \mathrm{Gr}^{[\pi']}(\mathbb{Q}).$$

This is the analogue of or $\mathbb{H} \cup \mathbb{P}^1(\mathbb{Q})$ in our first example, it is now more complicated because we have several Grassmannians, and we also have maps

$$r_{\pi_1,\pi_2} \mathrm{Gr}^{[\pi_1]}(\mathbb{Q}) \to \mathrm{Gr}^{[\pi_2]}(\mathbb{Q}) \text{ if } \pi_2 \subset \pi_1.$$

Our first aim is to put a topology on this space such that $\Gamma\backslash\overline{X}$ becomes a compact Hausdorff space.

In our first example we interpreted the Farey circle $D\left(c, \frac{p}{q}\right)$ with $0 < c < 1$ as an open subset of points in $\mathbb{H}$, which are close to the point $\frac{p}{q}$, but far away from any other point in $\mathbb{P}^1(\mathbb{Q})$.

The point of reduction theory is that for any parabolic $P \in \mathrm{Gr}^{[\pi']}(\mathbb{Q})$ (here we also allow $P = G$) we define open sets

$$X^P(\underline{c}_{\pi'}, r(\underline{c}_{\pi'})) \subset X \tag{1.29}$$

which depend on certain parameters $\underline{c}_P, r(\underline{c}_P))$ The points in $X^P(\underline{c}_{\pi'}, r(\underline{c}_{\pi'}))$ should be viewed as the points, which are "very close" to the parabolic subgroup P (controlled by $\underline{c}_{\pi'}$) but "keep a certain distance" (controlled by $r(\underline{c}_{\pi'})$) to the parabolic subgroups $Q \not\supset P$. They are the analogues of the Farey circles. We will see:

a)This system of open sets is invariant under the action $\mathrm{Gl}_n(\mathbb{Z})$

b) For $P = G$ the set $X^G(\emptyset, r_0)$ is relatively compact modulo the action of $\mathrm{Gl}_n(\mathbb{Z})$.

c) Any subgroup $\Gamma \subset \mathrm{Gl}_n(\mathbb{Z})$ has only finitely many orbits on any $\mathrm{Gr}^{[\pi']}(\mathbb{Q})$

d) For a suitable choice of the the parameters $\underline{c}_{\pi'}$, and $r(\underline{c}'_\pi)$ we have :

$$X = \bigcup_P X^P(\underline{c}_{\pi'}, r_{\underline{c}'_\pi}) = X^G(\emptyset, r_0) \cup \bigcup_{P:P\text{proper}} X^P(\underline{c}_{\pi'}, r(\underline{c}_{\pi'}))$$

and if P and P_1 are conjugate and $P \neq P_1$ then $X^P(\underline{c}'_\pi, r(\underline{c}_{\pi'})) \cap X^{P_1}(\underline{c}_{\pi'}, r(\underline{c}_{\pi'})) = \emptyset$.

Let us assume that we have constructed such a system of open sets, then c) and d) impliy that for a given type π' we have

$$\Gamma\backslash \bigcup_{P:\text{type}(\pi')=\pi} X^P(\underline{c}'_\pi, r(\underline{c}_{\pi'})) = \bigcup \Gamma_{P_i}\backslash X^{P_i}(\underline{c}'_\pi, r(\underline{c}_{\pi'}))$$

where $\{\dots, P_i, \dots\} = \Sigma(\pi, \Gamma)$ is a set of representatives of $\mathrm{Gr}^{[\pi']}(\mathbb{Q})$ modulo the action of Γ and $\Gamma_{P_i} = \Gamma \cap P_i(\mathbb{Q})$.

This tells us that we have a covering

$$\Gamma\backslash X = \Gamma\backslash X^G(\emptyset, r_0) \cup \bigcup_{\pi'\neq\emptyset} \bigcup_{P\in\Sigma(\pi',\Gamma)} \Gamma_P\backslash X^P(\underline{c}_{\pi'}, r(\underline{c}_{\pi'})) \tag{1.30}$$

The essential points of the philosophy of reduction theory are that $\Gamma\backslash X^G(\emptyset, r_0)$ *is relatively compact and that we have an explicit description of the sets* $\Gamma_P\backslash X^P(\underline{c}'_\pi, r(\underline{c}_{\pi'}))$ *as fiber bundles with nil manifolds as fiber over the locally symmetric spaces* $\Gamma_M\backslash X^M$.

We give the definition of the sets $X^P(\underline{c}'_\pi, r(\underline{c}'_\pi)$. We stick to the case that $G = \mathrm{Gl}_n/\mathbb{Q}$ and $\Gamma \subset \Gamma_0 = \mathrm{Gl}_n(\mathbb{Z})$. is a (congruence) subgroup of finite index. We defined the positive definite bilinear form (See 1.11)

$$\tilde{B}_{\Theta_x} = -\frac{1}{2n} B_{\Theta_x} : \mathfrak{g}_\mathbb{R} \times \mathfrak{g}_\mathbb{R} \to \mathbb{R}$$

and we have the identification $\mathfrak{g}_\mathbb{R} \xrightarrow{\sim} T_e^{\mathbb{G}(\mathbb{R})}$, and hence we get a euclidian metric on the tangent space $T_e^{\mathbb{G}(\mathbb{R})}$ at the identity e. This extends to a left invariant Riemannian metric on $G(\mathbb{R})$, we denote it by $d_{\Theta_x}s^2$. Hence we get a volume form $d^{\Theta_x}_{\mathrm{vol_H}}$ on any closed subgroup $H(\mathbb{R}) \subset G(\mathbb{R})$.

For any point $x \in X$ and any parabolic subgroup $P/\mathbb{Q}$ with unipotent radical $U/\mathbb{Q})$ we define

$$p_P(x, P) = \mathrm{vol_U}^{\Theta_x}(\Gamma_0 \cap U(\mathbb{R}))\backslash U(\mathbb{R})) \tag{1.31}$$

For the Arakelow-Chevalley scheme $(\mathrm{Gl}_n/\mathbb{Z}, \Theta_0)$ See(1.1.4) we have that $\tilde{B}_{\Theta_0}(E_{i,j}) = 1$. We have by construction

$$U_{i,j}(\mathbb{Z})\backslash U_{i,j}(\mathbb{R}) = \mathbb{R}/\mathbb{Z} \tag{1.32}$$

and under this identification $E_{i,j}$ maps to $\frac{\partial}{\partial x}$. Hence we get

$$d^{\Theta_0}_{\mathrm{vol_{U_{i,j}}}}(U_{i,j}(\mathbb{Z})\backslash U_{i,j}(\mathbb{R})) = 1$$

and from this we get immediately

Proposition 1.2.1. *For any parabolic subgroup P_0 containing the torus T_0 we have*

$$p_P(\Theta_0, P_0) = 1.$$

Let $(L, <\ ,\ >_x)$ be an Arakelow vector bundle and $(\mathrm{Gl}_n, \Theta_x)$ the corresponding Arakelow group scheme (of type Gl_n) let

$$\mathcal{F}_{\mathbb{Z}} : (0) = \{(0)\} = L_0 \subset L_1 \subset L_2 \subset \ldots \subset L_k = L = \mathbb{Z}^n$$

be a flag and $P/\mathbb{Z}$ the corresponding parabolic subgroup. Then we have the homomorphism

$$r_P : P/\operatorname{Spec}(\mathbb{Z}) \to M/\mathbb{Z} = \prod_{i=1}^{i=k} \mathrm{Gl}(L_i/L_{i-1}) \tag{1.33}$$

with kernel $U_P/\mathbb{Z}$. The metric $<\ ,\ >_x$ on $L \otimes \mathbb{R}$ yields an orthogonal decomposition

$$L \otimes \mathbb{R} = \bigoplus_{i=1}^{i=k} L_i/L_{i-1} \otimes \mathbb{R}$$

and hence an Arakelow bundle structure $(L_i/L_{i-1}, (\Theta_x)_i)$ for all i, and therefore an Arakelow group scheme structure on $M/\mathbb{Z}$.

Hence we get

Proposition 1.2.2. *If* (Gl_n, Θ) *is an Arakelow group scheme then* Θ *induces an Arakelow group scheme structure* Θ^M *on any reductive quotient* $M = P/U$.

Definition : A pair $(\mathrm{Gl}_n/\mathbb{Z}, \Theta)$ is called stable (resp. semi stable) if for any proper parabolic subgroup $P/\mathbb{Q} \subset \mathrm{Gl}_n/\mathbb{Q}$ we have

$$p_P(\Theta, P) > 1 \tag{1.34}$$

In our example in (1.2.2) the stable points are those outside the union of the closed Farey circles.

To get a better understanding of these numbers we have to do some computations with roots and weights. Let us start from an Arakelow vector bundle $(L = \mathbb{Z}^d, <\ ,\ >)$ and let us assume that L is equipped with a complete flag

$$\mathcal{F}_0 = \{0)\} = L_0 \subset L_1 \subset \cdots \subset L_{d-1} \subset L_d \tag{1.35}$$

which defines a Borel subgroup $B/\mathbb{Z}$. The quotients $(L_i/L_{i-1}, <\ ,\ >_i)$ are Arakelow line bundles over $\mathbb{Z}$ or in a less sophisticated language they are free modules of rank one and the generating vector $\bar{e}_i$ has a length $\sqrt{<\bar{e}_i, \bar{e}_i>_i}$. This length is of course also the volume of $(L_i/L_{i-1} \otimes \mathbb{R})/(L_i/L_{i-1})$.

The unipotent radical $U/\mathbb{Z} \subset B/\mathbb{Z}$ has a filtration $\{(0)\} \subset V_1 \subset \ldots, V_{n(n-1)/2-1} \subset V_{n(n-1)/2} = U$ by normal subgroups, the successive quotients are isomorphic to $\mathbb{G}_a$ and the torus $T = B/U$ acts by a positive root $\alpha_{i,j}$ and this is a one to one correspondence between the subquotients and the positive roots. Then it is clear: If ν corresponds to (i,j) then

$$(V_\nu/V_{\nu+1}, \Theta_\nu) = (L_i/L_{i-1}, <\ ,\ >_i) \otimes (L_j/L_{j-1}, <\ ,\ >_j)^{-1}. \tag{1.36}$$

Moreover the quotients $(V_\nu/V_{\nu+1},\Theta_\nu)$ depend only on the conformal class of $<\ ,\ >$ and hence only on the resulting Cartan involution Θ.

The unipotent subgroup $U/\mathbb{Z}$ contains the one parameter subgroup $U_{i,j}/Z$ and this one parameter subgroup maps isomorphically to $(V_\nu/V_{\nu+1})$. Hence our construction defines the Arakelow line bundle $(U_{i,j},\Theta_{i,j})$.

If we now define $n_{\alpha_{i,j}}(x,B)=\ \mathrm{vol}_{\Theta_{i,j}}(U_{i,j}(\mathbb{R})/U_{i,j}(\mathbb{Z}))$ then it is clear that

$$p_B(x,B)=\prod_{i<j} n_{\alpha_{i,j}}(x,B) \tag{1.37}$$

If $P\supset B$ then its unipotent radical $U_P\subset U$ and we defined the set Δ^{U_P} as the set of positive roots for which $U_{i,j}\subset U_P$. Then we have

$$p_P(x,P)=\prod_{(i,j)\in\Delta^{U_P}} n_{\alpha_{i,j}}(x,B) \tag{1.38}$$

Here it is important to notice the right hand side does not depend on the choice of $B\subset P$.

We follow a convention and put $2\rho_P=\sum_{(i,j)\in\Delta^{U_P}}\alpha_{i,j}$ so that ρ_P is the half sum of positive roots in in the unipotent radical. This character is equal to γ_P in formula (1.28) and hence we know for any maximal parabolic subgroup P_{i_0}

$$2\rho_{P_{i_0}}=\sum_{i\le i_0,j\ge i_0+1}\alpha_{i,j}=n\gamma_{i_0} \tag{1.39}$$

Since the numbers $n_{\alpha_{i,j}}(x,B)$ are positive real numbers we define for any $\gamma=\sum x_i\alpha_{i,i+1}\in X^*(T)\otimes\mathbb{R}$

$$n_\gamma(x,B)=\prod_{i=1}^{n-1} n_{\alpha_{i,j}}(x,B)^{x_i}. \tag{1.40}$$

Here we see that the second argument is a Borel-subgroup B. But if the above character $\gamma: B(\mathbb{R})\to\mathbb{R}^\times_{>0}$ extends to a character $\gamma: P(\mathbb{R})\to\mathbb{R}^\times_{>0}$ (See above (1.42)) the we can define

$$n_\gamma(x,P):=n_\gamma(B)$$

and this number only depends on P and not on the Borel subgroup $B\subset P$. The characters which extend are exactly the linear combinations (See (1.42)) $\gamma=\sum_{\alpha_i\in\pi^U}x_i\gamma_i$. The charactere $\gamma_P=\sum_{\alpha_i\in\pi^U}r_i\gamma_i$ where the $r_i>0$ are rational numbers. Hence the formula (**??**) implies

$$p_P(x,P)=\prod_{\alpha_i\in\pi^U} n_{\gamma_i}(x,P_i)^{r_i}=\prod_{\alpha_i\in\pi^U} p_{P_i}(x,P_i)^{\frac{r_i}{n}} \tag{1.41}$$

The Arakelow scheme $(\mathrm{Gl}_n/\mathbb{Z},\Theta)$ *is stable if for all maximal parabolic subgroups* $p_{P_i}(\Theta,P_i)=n_{\gamma_i}(\Theta,P_i)^n>1$.

We need a few more formulas relating roots and weights. For any parabolic subgroup we have the division of the set of simple roots into two parts

$$\pi=\pi^M\cup\pi^{U_P}.$$

This induces a splitting of the character module $\boxed{\text{split}}$

$$X^*(T)\otimes\mathbb{Q} = \bigoplus_{\alpha_i\in\pi^M}\mathbb{Q}\alpha_i \oplus \bigoplus_{\alpha_i\in\pi^{U_P}}\mathbb{Q}\gamma_i \tag{1.42}$$

where γ_i is the dominant fundamental weight attached to α_i (See (1.27)).

If now $\alpha_i \in \pi^{U_P}$ then we can project α_i to the second component, this projection

$$\alpha_i^P = \alpha_i + \sum_{\alpha_\nu\in\pi^M} c_{i,\nu}\alpha_\nu \tag{1.43}$$

Here an elementary - but not completely trivial - computation shows that

$$c_{i,\nu}\geq 0 \tag{1.44}$$

Since $\alpha_i^P \in \oplus\bigoplus_{\alpha_i\in\pi^{U_P}}\mathbb{Q}\gamma_i$ these characters extend and hence $n_{\alpha_i^P}(x,P)$ is defined.

We state the two fundamental theorems of reduction theory

Theorem 1.2.1. *For any Arakelow group scheme* (Gl_n,Θ) *we can find a Borel subgroup* $B\subset \mathrm{Gl}_n$ *for which*

$$n_{\alpha_i}(\Theta,B) < \frac{2}{\sqrt{3}} \text{ for all } i=1,\dots,n-1$$

Theorem 1.2.2. *For any Arakelow group scheme* (Gl_n,Θ) *we can find a a unique parabolic subgroup* P *such that for all* $\alpha_i\in\pi^{U_P}$ *we have*

$$n_{\alpha_i^P}(\Theta,P)<1$$

and such that the reductive quotient (M,Θ^M) *is semi stable.*

The first theorem is due to Minkowski, the second theorem is proved in [Stu], [Gray].

This parabolic subgroup is called the canonical destabilizing group. If (G,x) is semi stable then $P=G$. We denote it by $P(x)$. This gives us a dissection of X into the subsets

$$X = \bigcup_{P\text{: parabolic subgroups of } G/\mathbb{Q}} X^{[P]} = \{x\in X \mid P(x)=P\} \tag{1.45}$$

Clearly $\gamma X^{[P]} = X^{\gamma P\gamma^{-1}]}$ If we divide by the group Γ the we get

$$\Gamma\backslash X = \bigcup_{P\in Par}\Gamma_P\backslash X^{[P]} \tag{1.46}$$

where *Par* (Γ) is a set of representatives of Γ conjugacy classes of parabolic subgroups of $\mathrm{Gl}_n/\mathbb{Q}$. This is a decomposition of $\Gamma\backslash X$ into a disjoint union of subsets. The subset $\Gamma\backslash X^{[\mathrm{Gl}_n]}$ is compact, it is the set of semi stable pairs (x,Gl_n), the subsets $\Gamma_P\backslash X^{[P]}$ for $P\neq G$ are in a certain sense "open in some directions" and "closed in some other direction". Therefore this decomposition is not so useful for the study of cohomology groups.

Do remedy this we introduce larger subsets. For a real number $r, 0 < r < 1$ we define $\boxed{\text{Gstable}}$

$$X^{\mathrm{Gl}_n}(r) = \{x \in X | \, n_{\gamma_\alpha}(x, P(x)) > r, \text{ for all } \alpha \in \pi^{U_{P(x)}}). \tag{1.47}$$

It contains the set of semi-stable (x, Gl_n). If we choose $r < 1$ but close to one then the the elements in $X^{\mathrm{Gl}_n}(r)$ are only a "little bit unstable".

Together with the first theorem this has a consequence

Proposition 1.2.3. *The quotient $X^{\mathrm{Gl}_n}(r) = \Gamma \backslash X^{\mathrm{Gl}_n}(r)$ is relatively compact open subset of $\Gamma \backslash X$, It contains the set of semi-stable (x, Gl_n).*

We start from a parabolic subgroup P and let $M = P/U_P$ be its Levi-quotient. Our considerations above also apply to $M/\mathbb{Q}$. The group $P(\mathbb{R})$ acts transitively on X and we put

$$X^M = U_P(\mathbb{R}) \backslash X \text{ and } q_M : X \to X^M \text{ is the projection}$$

the is the (generalized) symmetric space attached to the reductive group $M/\mathbb{Q}$. For a simple roots $\alpha \in \pi^M$, a Borel subgroup $\bar{B} \subset M/\mathbb{Q}$ and a point $x^M = q_M(x)$ we can define the numbers $n_\alpha(x^M, \bar{B})$ essentially in the same way as before and clearly

$$n_\alpha(x^M, \bar{B}) = n_\alpha(x, B)$$

if B is the inverse image of $\bar{B}$.

We have to be a little bit careful with the numbers $p_{\bar{Q}}(x^M, \bar{Q})$ because the for the inverse image Q the unipotent radical U_Q is larger than $U_{\bar{Q}}$. Therefore we have to look at the dominant fundamental weights $\gamma_\alpha^M \in \bigoplus_{\alpha_i \in \pi^M} \mathbb{Q}\alpha_i$, and formulate the stability condition for x^M in terms of these γ_α^M :

The point x^M is stable, if for all $_{\alpha_i \in \pi^M}$ the inequality $n_{\gamma^M_{\alpha_i}}(x^M, \bar{P}_{\alpha_i}) > 1$ holds. Again we denote the destabilizing group by $P(x^M)$

Hence we see that for a number $r_M < 1$ we can define regions

$$X^M(r_M) = \{x^M | n_{\gamma^M_{\alpha_i}}(x^M, \bar{P}_{\alpha_i}) > r_M \text{ whenever } \bar{P}_{\alpha_i} \supset \bar{P}(x^M)\}$$

We choose vectors $\underline{c}_P = (\dots, c_\alpha, \dots)_{\alpha \in \pi^{U_P}}$ where all $0 < c_\alpha < 1$. Furthermore we choose a number $r(\underline{c}_P) < 1$ and define

$$X^P(\underline{c}_P, r(\underline{c}_P)) = \{x | \, n_{\alpha^P}(x, P) < c_\alpha \text{ for all } \alpha \in \pi^{U_P}; x^M \in X^M(r(\underline{c}_P))\} \tag{1.48}$$

Proposition 1.2.4. *For a given $r(\underline{c}_P) < 1$ we can find arrays $\underline{c}_P$ such that that for any $x \in X^P(\underline{c}_P, r(\underline{c}_P))$ the destabilizing parabolic subgroup $P(x) \subset P$. The same is true in the other direction: Given $\underline{c}_P$ we can find $r < 1$ such that for $x \in X^P(\underline{c}_P, r))$ the de-stabilizing parabolic subgroup $P(x) \subset P$.*

To see this we have to look at the canonical subgroup $\bar{Q} \subset (x_M, M)$. Its inverse image $Q \subset P$ is a parabolic subgroup of Gl_n. The reductive quotient $(x_{\bar{M}}, \bar{M})$ is semi- stable. We want to show that Q is the canonical parabolic of (x, Gl_n), for this we have to show that $n_{\alpha^Q}(x, Q) < 1$ for all $\alpha \in \pi^{U_Q} = \pi^{U_P} \cup \pi^{M,U_{\bar{Q}}}$.

For $\alpha \in \pi^{M,U_{\bar{Q}}}$ this is true by definition. For $\alpha \in \pi^{U_P}$ we have

$$\alpha^P = \alpha + \sum_{\beta \in \pi^M} a_{\alpha,\beta}\beta \text{ and } \alpha^Q = \alpha + \sum_{\beta \in \pi^{\bar{M}}} a'_{\alpha,\beta}\beta,$$

where $a_{\alpha,\beta} \geq 0$. The roots $\beta \in \pi^{M,U_{\bar{Q}}}$ can be expressed in terms of the $\beta^{\bar{Q}} = \beta^Q$:

$$\beta^Q = \beta + \sum_{\beta' \in \pi^{\bar{M}}} a^*_{\beta,\beta'}\beta' \tag{1.49}$$

and hence

$$\alpha^Q = \alpha^P - \sum_{\beta \in \pi^{M,U_{\bar{Q}}}} a_{\alpha,\beta}\beta^Q + \sum_{\beta' \in \pi^{\bar{M}}} c_{\alpha\beta'}\beta'. \tag{1.50}$$

The last sum is zero because $\alpha^Q, \alpha^P, \beta^Q$ are orthogonal to the module $\oplus_{\beta'}\mathbb{Z}\beta'$.

We get the relation

$$n_{\alpha^Q}(x, Q) = n_{\alpha^P}(x, P) \cdot \prod_{\beta \in \pi^{M,U_{\bar{Q}}}} n_{\beta^Q}(x, Q)^{-a_{\alpha,\beta}}. \tag{1.51}$$

Now it comes down to show that $\boxed{\text{wc}}$

$$\begin{gathered} n_{\alpha^P}(x, P) < c_\alpha,\ \forall\ \alpha \in \pi^{U_P} \text{ and } n_{\beta^Q}(x, Q) > r,\ \forall \beta\ \in \pi^{M,U_{\bar{Q}}} \\ \text{implies } n_{\alpha^Q}(x, P) < 1\,; \forall\ \alpha \in \pi^{U_P} \end{gathered} \tag{1.52}$$

This is certainly true if either the c_α are small enough or if r is sufficiently close to one.

We claim that we can find a family of parameters

$$(\dots, \underline{c}_P, \dots)_{P:\text{ parabolic over } \mathbb{Q}}, r(\underline{c}_P)$$

where $(\underline{c}_P, r(\underline{c}_P))$ only depend on the type of P, which satisfy (1.52) such that we get a covering

$$X = \bigcup_P X^P(\underline{c}_P, r(\underline{c}_P)))$$

and hence

$$\Gamma\backslash X = \bigcup_P \Gamma_P\backslash X^P(\underline{c}_P, r(\underline{c}_P)).$$

The condition (1.52) says that two sets of inequalities imply a third one. If $P = G$ then the first set of inequalities is empty and if $P/\mathbb{Q}$ is minimal that the second set of inequalities is empty. We start from $P = \mathrm{Gl}_n$, in this case $\pi^{U_P} = \emptyset$ and we choose a small positive number $r_0 < 1$ and put $c(\emptyset) = r_0$. Now we look at the maximal parabolic subgroups. Again we choose a number $0 < r_1 < 1$. For all the maximal parabolic subgroups P_i of type α_i we can find a $(c_{P_i}) < 1$ such that $(c_{P_i}), r_1)$ is well chosen. We know of course that

$$X = X^{\mathrm{Gl}_n}(\emptyset, r_0) \cup X^{P_i}((1), r_1)$$

here we have replaced c_{P_i} by 1 and we may have lost (1.52).. Hence we have to loo look for the points

$$x \in X^{P_i}((1), r_1) \setminus X^{P_i}((c_{P_i}), r_1)$$

We consider the parabolic subgroups $P_{i,j} \subset P_i$ they are of type $\pi' = \{\alpha_i, \alpha_j\}$

Therefore we now constructed the covering which satisfies the necessary requirements. Since the $\underline{c}_P, r(\underline{c}_P)$ only depend on the type of P, we change the notation: $\underline{c}_P \to \underline{c}'_\pi, r(\underline{c}_P) \to r(\underline{c}'_\pi)$.

We have a very explicit description of these sets $\Gamma_P \backslash X^P(\underline{c}'_\pi, r(\underline{c}'_\pi))$. We consider the evaluation map

$$\begin{gathered} n^{\pi'} : \Gamma_P \backslash X^P(\underline{c}'_\pi, r(\underline{c}'_\pi)) \to \textstyle\prod_{\alpha \in \pi'}(0, c_\alpha) \\ x \mapsto (\dots, n_{\alpha^P}(x, P), \dots) \end{gathered} \tag{1.53}$$

Of course we also have the homomorphism

$$|\alpha^{\pi'}| : P(\mathbb{R}) \to \{\dots, |\alpha^P|, \dots\}_{\alpha \in \pi'} \tag{1.54}$$

and the multiplication by an element $y \in P(\mathbb{R})$ induces an isomorphisms of the fibers

$$(n_X^{[\pi']})^{-1}(c_1) \xrightarrow{\sim} (n_X^{[\pi']})^{-1}(c_2) \text{ if } |\alpha^{\pi'}|(y) \cdot c_1 = c_2$$

where the multiplication is taken componentwise. This identification depends on the choice of y.

To get a canonical identification we use the geodesic action which is introduced in the paper by Borel and Serre. We define an action of $A = (\prod_{\alpha \in \pi\pi'} \mathbb{R}^\times_{>0})$ on X. This action depends on P and we denote it by

$$(a, x) \mapsto a \bullet x$$

A point $x \in X$ defines a Cartan involution Θ_x and then the parabolic subgroup P^{Θ_x} of $G \times \mathbb{R}$ is opposite to $P \times \mathbb{R}$ and $P \times \mathbb{R} \cap P^{\Theta_x} = M_x$ is a Levi factor, the projection $P \to M$ induces an isomorphism

$$\phi_x : M \times \mathbb{R} \xrightarrow{\sim} M_x.$$

The character $\alpha^{\pi'}$ induces an isomorphism

$$s_x : A \xrightarrow{\sim} S_x(\mathbb{R})^{(0)}$$

where Hence we $S_x(\mathbb{R})^{(0)}$ is the connected component of the identity of the center $M_x(\mathbb{R}) \cap \mathrm{Sl}_n(\mathbb{R})$ and we put

$$a \bullet x = s_x(a)x$$

We have to verify that this is indeed an action. This is clear because for the Cartan-involution $\Theta_{a\bullet x}$ we obviously have

$$P^{\Theta_x} = P^{\Theta_{a\bullet x}}.$$

It is also clear that this action commutes with the action of $P(\mathbb{R})$ on X because

$$ys_x(a)x = s_{yx}(a)yx \text{ for all } y \in P(\mathbb{R}), x \in X.$$

It follows from the construction that the semigroup $A_- = \{\dots, a_\nu, \dots\}$- where $0 < a_\nu \leq 1$ - acts via the geodesic action on $X^P(c_\pi, r(\underline{c}_{\pi'}))$ and that for $a \in A_-$ we get an isomorphism

$$(n^{[\pi']})^{-1}(c_1) \xrightarrow{\sim} (n^{[\pi']})^{-1}(ac_1).$$

This yields a decomposition as product

$$X^P(c'_\pi, r(\underline{c}_{\pi'})) = (n^{[\pi']})^{-1}(c_0) \times \prod_{\alpha\in\pi'} (0, c_\alpha]$$

where c_0 is an arbitrary point in the product.

Since we know that $|\alpha^{\pi'}|$ is trivial on Γ_P and since the action of P commutes with the geodesic action we conclude

$$\Gamma_P\backslash X^P(c'_\pi, r(\underline{c}_{\pi'})) = \Gamma_P\backslash(n^{\pi'})^{-1}(c_0) \times \prod_{\alpha\in\pi'} (0, c_\alpha] \tag{1.55}$$

Let $P^{(1)}(\mathbb{R}) = \ker(\alpha^{\pi'})$ then the fiber $(n^{\pi'})^{-1}(c_0)$ is a homogenous space under $P^{(1)}(\mathbb{R})$ We have the projection map $p_{P,M} : X \to X^M$ where X^M is the space of Cartan involutions on the reductive quotient M. Hence we get a map

$$p^*_{P,M} = p_{P,M} \times n^{[\pi']} : X \to X^M \times \prod_{\alpha\in\pi'} (0, c_\alpha] \tag{1.56}$$

On the product $X^M \times \prod_{\alpha\in\pi'}(0, c_\alpha]$ the geodesic action only acts on the second factor the map $p^*_{P,M}$ commutes with the geodesic action.

The group $U_P(\mathbb{R})$ acts simply transitively on the fibers of this projection, and hence

$$q_{P,M} : \Gamma_P\backslash X^P(c'_\pi, r(\underline{c}_{\pi'})) \to \Gamma_M\backslash X^M(r(\underline{c}_P)) \times \prod_{\alpha\in\pi'} (0, c_\alpha] \tag{1.57}$$

is a fiber bundle with fiber isomorphic $\Gamma_U\backslash U(\mathbb{R})$. If we pick a point $\tilde{x} \in \Gamma_M\backslash X^M(r(\underline{c}_P))\times \prod_{\alpha\in\pi'}(0, c_\alpha]$ then the identification of $q^{-1}_{P,M}(\tilde{x})$ with $\Gamma_U\backslash U(\mathbb{R})$ depends on the choice of a point $x \in X^P(c'_\pi, r(\underline{c}_{\pi'}))$ which maps to $\tilde{x}$.

(**The next requires a little revision)** This can now be compactified, we embed it into

$$\overline{\Gamma_P\backslash X^P(c'_\pi, r(\underline{c}_P)} = \Gamma_P\backslash(n^{[\pi']})^{-1}(c_0) \times \prod_{\nu\in\pi_G\backslash\pi} [0, c'_\pi].$$

We define

$$\partial\overline{r(\underline{c}_P)} = \overline{\Gamma_P\backslash X^P(c'_\pi, \Omega_\pi)} \setminus \Gamma_P\backslash X^P(c_\pi, \Omega_\pi)$$

this is equal to

$$\partial\overline{\Gamma_P\backslash X^P(c'_\pi, r(\underline{c}_P)} = \Gamma_P\backslash (n^{[\pi]})^{-1}(c_0) \times \partial(\prod_{\nu\in\pi_G\backslash\pi}[0,c_\pi])$$

where of course $\partial(\prod_{\nu\in\pi_G\backslash\pi}[0,c_\pi]) \subset \prod_{\nu\in\pi_G\backslash\pi}[0,c_\pi]$ is the subset where at least one of the coordinates is equal to zero.

We form the disjoint union of of these boundaries over the π and set of representatives of Γ conjugacy classes, this is a compact space. Now there is still a minor technical point. If we have two parabolic subgroups $Q \subset P$ then the intersection $X^P(\underline{c}_P, r(\underline{c}_P) \cap X^Q(\underline{c}_Q, r(\underline{c}_Q)) \neq \emptyset$. If we now have points

$$x \in \partial\overline{\Gamma_P\backslash X^P(c_\pi, r(\underline{c}_P)}, y \in \partial\overline{\Gamma_Q\backslash X^Q(c_{\pi'}, r(\underline{c}_{P'})}$$

then we identify these two points if we have a sequence of points $\{x_n\}_{n\in\mathbb{N}}$ which lies in the intersection $X^P(c_\pi, r(\underline{c}_P)) \cap X^Q(c_{\pi'}, r(\underline{c}_{P'}))$ and which converges to x in $\overline{\Gamma_P\backslash X^P(c_\pi, r(\underline{c}_P)}$ and to y in $\overline{\Gamma_Q\backslash X^Q(c_{\pi'}, r(\underline{c}_{P'})}$. A careful inspection shows that this provides an equivalence relation $\sim$, and we define

$$\partial(\Gamma\backslash X) = \bigcup_{\pi', P\in\mathrm{Par}(\Gamma)} \partial\overline{\Gamma_P\backslash X^P(c_\pi, r(\underline{c}_P)}/\sim$$

and the Borel-Serre compactification will be the manifold with corners

$$\overline{\Gamma\backslash X} = \Gamma\backslash(X \cup \bigcup_{P:P\text{proper}} \overline{X^P(\underline{c}_{\pi'}, r(\underline{c}_P)}). \tag{1.58}$$

We define a "tubular" neighborhood of the boundary we put

$$\mathcal{N}(\Gamma\backslash X) = \Gamma\backslash \bigcup_{P:P\text{proper}} \overline{X^P(\underline{c}_{\pi'}, r(\underline{c}_P)}) \tag{1.59}$$

and then we define the "punctured tubular" neighborhood as

$$\overset{\bullet}{\mathcal{N}}(\Gamma\backslash X) = \Gamma\backslash \bigcup_{P:P\text{proper}} X^P(\underline{c}_{\pi'}, r(\underline{c}_P)) = \Gamma\backslash X \cap \mathcal{N}(\Gamma\backslash X) \tag{1.60}$$

Eventually we want to use the above covering as a tool to understand cohomology (See) But then it is also necessary to understand the intersections

$$X^{P_1}(c_{\pi_1}, r(\underline{c}_{\pi_1})) \cap \cdots \cap X^{P_\nu}(c_{\pi_\nu}, r(\underline{c}_{\pi_\nu})) \tag{1.61}$$

Our proposition 1.2.4 implies that for any point x in the intersection the destabilizing parabolic subgroup $P(x) \subset P_1 \cap \cdots \cap P_\nu$. Hence we see that the above intersection can only be non empty if $Q = P_1 \cap \cdots \cap P_\nu$ is a parabolic subgroup.

Now we look at the product $\prod_{\alpha\in\pi} \mathbb{R}^\times_{>0}$ here it seems to be helpful to identify it - using the logarithm - with $\mathbb{R}^d$:

$$\log : \prod_{\alpha\in\pi} \mathbb{R}^\times_{>0} \xrightarrow{\sim} \mathbb{R}^d \tag{1.62}$$

If G is one of our reductive groups Gl_n, M let X be the symmetric space of Cartan involutions- If we have a point $x \in X$ and P a parabolic subgroup such that $P(x) \subset P$ then the number $n_{\alpha P}(x,P)$ is defined and < 1. If $P(x) \not\subset P$ then we put $n_{\alpha P}(x,P) = 1$, so that $n_{\alpha P}(x,P)$ is always defined.

Hence we defined a function

$$N^Q(\ ,Q) : X \to \mathbb{R}^d; x \mapsto \{\dots, -\log(n_{\alpha^Q}(x,Q)), \dots\}_{\alpha\in\pi} = \{\dots, N_{\alpha^Q}(x,Q), \dots\}_{\alpha\in\pi}. \tag{1.63}$$

a close look shows that the image is a convex set $C(\underline{\tilde{c}}) \subset \mathbb{R}^d$ because it is an intersection of half spaces defined by hyperplanes. In the target space we can project to the unipotent roots, i.e. we look at the projection

$$r_Q : \underline{x} = \{\dots, x_\alpha, \dots\}_{\alpha\in\pi} \mapsto \{\dots, x_\alpha, \dots\}_{\alpha\in\pi^{U_Q}}.$$

Then we can consider the composition $r_Q \circ N^Q(\ ,Q)$ and the image under this composition is a cone $C_{U_Q}(\underline{\tilde{c}})$ in $\mathbb{R}^{d_1}_{>0}$.Then

$$X^{P_1}(c_{\pi_1}, r(\underline{c}_{\pi_1})) \cap \dots \cap X^{P_\nu}(c_{\pi_\nu}, r(\underline{c}_{\pi_\nu})) = X^Q(C(\underline{\tilde{c}})) \to C_{U_Q}(\underline{\tilde{c}}) \tag{1.64}$$

is a fiber bundle over the base $C_{U_Q}(\underline{\tilde{c}})$.

Chapter 2

The Cohomology groups

2.1 Cohomology of arithmetic groups as cohomology of sheaves on $\Gamma\backslash X$

We are now in the position to unify — for the special case of arithmetic groups — the two cohomology theories from our chapter II and chapter IV of the [book]. (Lectures on Algebraic Geometry I)

We start from a semi simple group $G/\mathbb{Q}$ and we choose an arithmetic subgroup $\Gamma \subset G(\mathbb{Q})$. Let $X = G(\mathbb{R})/K$ as before.

Let $\mathcal{M}$ is a Γ-module then we can attach a sheaf $\tilde{\mathcal{M}}$ onM$\Gamma\backslash X$ to it. To do this we have to define the group of sections for any open subset $U \subset X$. We start from the projection

$$\pi : X \longrightarrow \Gamma\backslash X$$

and define

$$\tilde{\mathcal{M}}(U) = \{f : \pi^{-1}(U) \to \mathcal{M} \mid f \text{ is locally constant } f(\gamma u) = \gamma f(u)\}.$$

This is clearly a sheaf. For any point $x \in \Gamma\backslash X$ we can find a neighborhood V_x with the following property: If $\tilde{x} \in \pi^{-1}(x)$, then $\tilde{x}$ has a contractible $\Gamma_{\tilde{x}}$-invariant neighborhood $U_{\tilde{x}}$ and $U_x = \Gamma_{\tilde{x}}\backslash U_{\tilde{x}}$. Then it is clear that

$$\tilde{\mathcal{M}}(V_x) = \mathcal{M}^{\Gamma_{\tilde{x}}}.$$

Since x has a cofinal system of neighborhoods of this kind, we see that we get an isomorphism

$$j_{\tilde{x}} : \tilde{\mathcal{M}}(V_x) = \tilde{\mathcal{M}}_x \xrightarrow{\sim} \mathcal{M}^{\Gamma_{\tilde{x}}}.$$

The last isomorphism depends on the choice of $\tilde{x}$. If we are in the special case that Γ has no fixed points then we can cover $\Gamma\backslash X$ by open sets U so that $\tilde{\mathcal{M}}/U$ is isomorphic to a constant sheaf $\underline{\mathcal{M}}_U$. These sheaves are called local systems.

We will denote the functor, which sends $\mathcal{M}$ to $\tilde{\mathcal{M}}$ by

$$\mathrm{sh}_\Gamma : \mathbf{Mod}_\Gamma \to \mathcal{S}_{\Gamma\backslash X},$$

occasionally we will write $\mathrm{sh}_\Gamma(\mathcal{M})$ instead of $\tilde{\mathcal{M}}$, especially in situations where we work with several discrete subgroups.

The motivations for these constructions are

1) The spaces $\Gamma\backslash X$ are interesting examples of so-called locally symmetric spaces (provided Γ has no torsion). Hence they are of interest for differential geometers and analysts.

2) If we have some understanding of the geometry of the quotient space $\Gamma\backslash X$ we gain some insight into the structure of Γ. This will become clear when we discuss the examples in ...x.y.z.

3) The cohomology groups $H^\bullet(\Gamma,\mathcal{M})$ are closely related and in many cases even isomorphic to the sheaf cohomology groups $H^\bullet(\Gamma\backslash X,\tilde{\mathcal{M}})$. Again the geometry provides tools to compute these cohomology groups in some cases (see x.y.z.).

4) If the Γ-module $\mathcal{M}$ is a $\mathbb{C}$-vector space and obtained from a rational representation of $G/\mathbb{Q}$, then we can apply analytic tools to get insight (de Rham cohomology, Hodge theory).

2.1.1 The relation between $H^\bullet(\Gamma,\mathcal{M})$ and $H^\bullet(\Gamma\backslash X,\tilde{\mathcal{M}})$.

In general the spaces X will have several connected components. In this section we assume that X is connected and Γ fixes it.

Then it is clear that

$$H^0(\Gamma\backslash X,\tilde{\mathcal{M}}) = \mathcal{M}^\Gamma.$$

Hence we can write our functor $\mathcal{M}\to\mathcal{M}^\Gamma$ from the category of Γ-modules to **Ab** as a composite of

$$\mathrm{sh}_\Gamma : \mathcal{M}\longrightarrow\tilde{\mathcal{M}} \text{ and } H^0:\tilde{\mathcal{M}}\to H^0(\Gamma\backslash X,\tilde{\mathcal{M}}).$$

We want to apply the method of spectral sequences. In a first step we want to convince ourselves that sh_Γ sends injective Γ-modules to acyclic sheaves.

In [book], 2.2.4. we constructed for any Γ module $\mathcal{M}$ the induced Γ -module $\mathrm{Ind}_{\{1\}}^\Gamma\mathcal{M}$. This is the module of functions $f:\Gamma\to\mathcal{M}$ and $\gamma_1\in\Gamma$ acts on this module by $(\gamma_1 f)(\gamma) = f(\gamma\gamma_1)$. We want to prove that for any such induced module the sheaf $\mathrm{sh}_\Gamma(\ \mathrm{Ind}_{\{1\}}^\Gamma\mathcal{M})$. is acyclic.

We have a little

Lemma: *Let us consider the projection $\pi : X\to\Gamma\backslash X$ and the constant sheaf $\underline{\mathcal{M}}_X$ on X. Then we have a canonical isomorphism of sheaves*

$$\pi_*(\underline{\mathcal{M}}_X)\xrightarrow{\sim}\widetilde{\mathrm{Ind}_{\{1\}}^\Gamma}\mathcal{M}.$$

Proof: This is rather obvious. Let us consider a small neighborhood U_x of a point x, such that $\pi^{-1}(U_x)$ is the disjoint union of small contractible neighborhoods $U_{\tilde{x}}$ for $\tilde{x}\in\pi^{-1}(x)$. Then for all points $\tilde{x}$ we have $\underline{\mathcal{M}}_X(U_{\tilde{x}}) = \mathcal{M}$ and

$$\pi_*(\underline{\mathcal{M}}_X)(U_x) = \prod_{\tilde{x}\in\pi^{-1}(x)}\mathcal{M}.$$

On the other hand

$$\widetilde{\mathrm{Ind}_{\{1\}}^\Gamma}\mathcal{M}(U_x) = \left\{h:\pi^{-1}(U_x)\to\ \mathrm{Ind}_{\{1\}}^\Gamma\mathcal{M}\mid h \text{ is locally constant } h(\gamma u) = \gamma h(u)\right\}$$

For $u \in \pi^{-1}(U_x)$ the element $h(u)$ itself is a map

$$f(u) : \Gamma \longrightarrow \mathcal{M},$$

and $(\gamma h(u))(\gamma_1) = h(u)(\gamma_1\gamma)$ (here $\gamma_1 \in \Gamma$ is the variable.)

Hence we know the function $u \to f(u)$ from $\pi^{-1}(U_x)$ to $\mathrm{Ind}_{\{1\}}^{\Gamma}\mathcal{M}$ if we know its value $f(u)(1)$ and this value can be prescribed on the connected components of $\pi^{-1}(U_x)$. On these connected components it is constant, we may take its value at $\tilde{x}$ and hence

$$f \longrightarrow (\ldots, f(\tilde{x})(1), \ldots)_{\tilde{x}\in\pi^{-1}(x)}$$

yields the desired isomorphism.

Now we get the acyclicity. We apply example d) in [book], 4.6.3 (section on application of spectral sequences) to this situation. The fibre of π is a discrete space and hence

$$\pi_*(\underline{\mathcal{M}}_X) = \widetilde{\mathrm{Ind}_{\{1\}}^{\Gamma}\mathcal{M}}$$

and $R^q(\pi_*)(\underline{\mathcal{M}}_X) = 0$ for $q > 0$. Therefore the spectral sequence yields

$$H^q(X, \underline{\mathcal{M}}_X) = H^q(\Gamma\backslash X, \pi_*(\underline{\mathcal{M}}_X)) = H^q\left(\Gamma\backslash X,\ \widetilde{\mathrm{Ind}_{\{1\}}^{\Gamma}\mathcal{M}}\right),$$

and since X is a cell, we see that this is zero for $q \geq 1$.

We apply this to the case that $m = \mathcal{I}$ is an injective Γ-module. Clearly we can always embed $\mathcal{I} \longrightarrow \mathrm{Ind}_{\{1\}}^{\Gamma}\mathcal{I}$. But this is now a direct summand; hence it follows from the acyclicity of $\widetilde{\mathrm{Ind}_{\{1\}}^{\Gamma}\mathcal{I}}$ that also $\tilde{\mathcal{I}}$ must be acyclic.

Hence we get a spectral sequence with E_2 term

$$H^p(\Gamma\backslash X, R^q(\mathrm{sh}_\Gamma)(\mathcal{M})) \Rightarrow H^n(\Gamma, \mathcal{M}).$$

The edge homomorphism yields a homomorphism

$$H^n(\Gamma\backslash X, \mathrm{sh}_\Gamma(\mathcal{M})) \to H^n(\Gamma, \mathcal{M})$$

which in general is neither injective nor surjective.

Of course it is clear that the stalk $R^q(\mathrm{sh}_\Gamma)(\mathcal{M})_x = H^q(\Gamma_{\tilde{x}}, \mathcal{M})$. If we make the assumption that the action of Γ is faithful, this means that any element γ different from the identity acts a non trivially on X, then $R^q(\mathrm{sh}_\Gamma)(\mathcal{M})$ is supported on a lower dimensional closed subset.

If we have a commutative ring R in which the orders of all the finite stabilizers $\Gamma_{\tilde{x}}$ are invertible and if we only consider $R-\Gamma$ modules $\mathcal{M}$, then of course $R^q(\mathrm{sh}_\Gamma)(\mathcal{M}) = 0$ for $q > 0$ and then the edge homomorphism becomes an isomorphism.

Functorial properties of cohomology

We investigate the functorial properties of the cohomology with respect to the change of Γ. If $\Gamma' \subset \Gamma$ is a subgroup of finite index, then we have, of course, the functor

$$\mathbf{Mod}_\Gamma \longrightarrow \mathbf{Mod}_{\Gamma'},$$

which is obtained by restricting the Γ-module structure to Γ'. Since for any Γ-module $\mathcal{M}$ we have $\mathcal{M}^\Gamma \longrightarrow \mathcal{M}^{\Gamma'}$, we obtain a homomorphism

$$\mathrm{res}\ : H^i(\Gamma, \mathcal{M}) \longrightarrow H^i(\Gamma', \mathcal{M}).$$

We give an interpretation of this homomorphism in terms of sheaf cohomology. We have the diagram

$$\begin{array}{ccc} & X & \\ \pi_{\Gamma'} \swarrow & & \searrow \pi_\Gamma \\ \pi_1 = \pi_{\Gamma,\Gamma'} : \Gamma' \backslash X & \longrightarrow & \Gamma \backslash X \end{array}$$

and a Γ-module $\mathcal{M}$ produces sheaves $\mathrm{sh}_\Gamma(\mathcal{M}) = \tilde{\mathcal{M}}$ and $\mathrm{sh}_{\Gamma'}(\mathcal{M}) \tilde{=} \mathcal{M}'$ on $\Gamma' \backslash X$ and $\Gamma \backslash X$ respectively. It is clear that we have a homomorphism

$$\pi_1^*(\tilde{\mathcal{M}}) \longrightarrow \tilde{\mathcal{M}}'.$$

To get this homomorphism we observe that for $y_1 \in \Gamma' \backslash X$ we have $\pi_1^*(\tilde{\mathcal{M}})_{y_1} = \tilde{\mathcal{M}}_{\pi_1(y_1)}$, and this is

$$\{f : \pi^{-1}(\pi_1(y)) \to \mathcal{M} \mid f(\gamma \tilde{y}) = \gamma f(\tilde{y}) \text{ for all } \gamma \in \Gamma, \tilde{y} \in \pi^{-1}(\pi(y_1))\}$$

and

$$\tilde{\mathcal{M}}'_{y_1} = \{fg : (\pi')^{-1}(y_1) \to \mathcal{M} \mid f(\gamma' \tilde{y}) = \gamma' f(\tilde{y}) \text{ for all } \gamma \in \Gamma', \tilde{y} \in (\pi')^{-1}(y_1)\},$$

and if we pick a point $\tilde{y} \in (\pi')^{-1}(y_1) \subset \pi^{-1}(\pi_1(y_1))$ then

$$\pi_1^*(\mathcal{M})_{y_1} \simeq \mathcal{M}^{\Gamma_{\tilde{y}_1}} \subset \tilde{\mathcal{M}}'_{y_1} = \mathcal{M}^{\Gamma'_{\tilde{y}_1}}.$$

Hence we get (or define) our restriction homomorphism as (see I, ...)

$$H^i(\Gamma \backslash X, \mathrm{sh}_\Gamma(\mathcal{M})) \longrightarrow H^i(\Gamma' \backslash X, \pi_1^*(\mathrm{sh}_\Gamma(\mathcal{M})) \longrightarrow H^i(\Gamma' \backslash X, \mathrm{sh}_{\Gamma'}(\mathcal{M})).$$

There is also a map in the opposite direction.
Since the fibres of π_1 are discrete we have

$$H^i(\Gamma' \backslash X, \tilde{\mathcal{M}}) \xrightarrow{\sim} H^i(\Gamma \backslash X, \pi_{1,*}(\tilde{\mathcal{M}})).$$

But the same reasoning as in the previous section yields an isomorphism

$$\pi_{1,*}(\tilde{\mathcal{M}}) \xrightarrow{\sim} \widetilde{\mathrm{Ind}_{\Gamma'}^\Gamma \mathcal{M}}.$$

Hence we get an isomorphism

$$H^i(\Gamma' \backslash X, \tilde{\mathcal{M}}) \xrightarrow{\sim} H^i(\Gamma \backslash X, \widetilde{\mathrm{Ind}_{\Gamma'}^\Gamma \mathcal{M}})$$

which is well known as Shapiro's lemma. But we have a Γ-module homomorphism

$$e: \operatorname{Ind}_{\Gamma'}^{\Gamma}\mathcal{M} \longrightarrow \mathcal{M}$$

which sends an $f : \Gamma \to \mathcal{M}$, in $f \in \operatorname{Ind}_{\Gamma'}^{\Gamma}\mathcal{M}$ to the sum

$$\operatorname{tr}(f) = \sum \gamma_i^{-1} f(\gamma_i)$$

where the γ_i are representatives for the classes of $\Gamma'\backslash\Gamma$. This homomorphism induces a map in the cohomology. We get a compositon

$$\pi_{1,\bullet} : H^i(\Gamma'\backslash X, \tilde{\mathcal{M}}) \longrightarrow H^i(\Gamma\backslash X, \tilde{\mathcal{M}}).$$

It is not difficult to check that

$$\pi_{1,\bullet} \circ \pi_1^\bullet = [\Gamma : \Gamma'].$$

2.1.2 How to compute the cohomology groups $H^i(\Gamma\backslash X, \tilde{\mathcal{M}})$?

The Čech complex of an orbiconvex Covering

We return to the beginning of this note. We want to find a finite set of points $\tilde{x}_1, \dots, \tilde{x}_i, \dots, \tilde{x}_r$ and open sets $\tilde{U}_{\tilde{x}_i}, \tilde{x}_i \in \tilde{U}_{\tilde{x}_i}$ such that the following conditions are true

a) For $\gamma \in \Gamma$ we have $\gamma\tilde{U}_{\tilde{x}_i} \cap \tilde{U}_{\tilde{x}_i} = \emptyset$ unless we have $\gamma\tilde{x}_i = \tilde{x}_i$, i.e. $\gamma \in \Gamma_{\tilde{x}_i}$

b) The map $\bigcup \tilde{U}_{\tilde{x}_i} \to \Gamma\backslash X$ is surjective

c) For all i we have a $\Gamma_{\tilde{x}_i}$ equivariant homotopy contracting $\tilde{U}_{\tilde{x}_i}$ to $\tilde{x}_i$.

d) For any non empty finite intersection $\dots \cap \tilde{U}_{\tilde{x}_i} \cap \dots \cap \tilde{U}_{\tilde{x}_j} \cap \dots$ we can find a point $\tilde{x}_{\underline{i}}$ in this intersection which is fixed by $\dots \cap \Gamma_{\tilde{x}_i} \cap \dots \Gamma_{\tilde{x}_j} = \Gamma_{\tilde{x}_{\underline{i}}}$ and such that we have a $\Gamma_{\tilde{x}_{\underline{i}}}$ equivariant homotopy contracting $\tilde{U}_{\tilde{x}_i}$ to $\tilde{x}_i$.

We know that the Čzech complex

$$C^\bullet(\mathfrak{U}, \tilde{\mathcal{M}}) \ := 0 \to \bigoplus_{i \in I} \tilde{\mathcal{M}}(U_{x_i}) \xrightarrow{d_0} \bigoplus_{i<j} \tilde{\mathcal{M}}(U_{x_i} \cap U_{x_j}) \to \tag{2.1}$$

computes the cohomology provided we know that the intersections $U_{\underline{i}} = U_{x_{i_1}} \cap U_{x_{i_2}} \cap \dots \cap U_{x_{i_q}}$ are acyclic, i.e. $H^m(U_{\underline{i}}, \tilde{\mathcal{M}}) = 0$ for $m > 0$.

For the implementation on a computer we need to resolve the definition of the spaces of sections and the definition of the boundary maps. (By this I mean that we have to write explicitly

$$\tilde{\mathcal{M}}(U_{\underline{i}}) = \bigoplus_{\eta} \mathcal{M}_\eta$$

where η runs through an index set and $\mathcal{M}_\eta$ are explicit subspaces of $\mathcal{M}$ and then we have to write down certain explicit linear maps $\mathcal{M}_\eta \to \mathcal{M}_{\eta'}$.)

To be more precise: We have to write $U_{\underline{i}} = \cup U_\eta$ as the union of its connected components, we have to choose a connected component $\tilde{U}_\eta$ in $\pi^{-1}(U_\eta)$ for each value of η, and then the evaluation of a section $m \in \tilde{\mathcal{M}}(U_{\underline{i}})$ on these $\tilde{U}_\eta$ yields an isomorphism

$$\oplus ev_{\tilde{U}_\eta} : \tilde{\mathcal{M}}(U_{\underline{i}}) \xrightarrow{\sim} \bigoplus_\eta \mathcal{M}^{\Gamma_\eta}.$$

If we replace $\tilde{U}_\eta$ by $\gamma\tilde{U}_\eta$ then we get for $m \in \tilde{\mathcal{M}}(\pi(\tilde{U}_\eta))$ the equality

$$\gamma ev_{\tilde{U}_\eta}(m) = ev_{\gamma\tilde{U}_\eta} \tag{2.2}$$

Especially the choice of the $\tilde{x}_i$ yields an identification

$$ev_{U_{x_i}} : \tilde{\mathcal{M}}(U_{x_i}) \xrightarrow{\sim} \mathcal{M}^{\Gamma_{\tilde{x}_i}} \tag{2.3}$$

this gives us the first term in the complex.

The computation of the second term is a little bit more delicate, the discussion in Chap.II is not correct. The point is that the intersections $U_{x_i} \cap U_{x_j}$ may not be connected. To get these connected components we have to find the elements $\gamma \in \Gamma$ for which

$$\tilde{U}_{\tilde{x_i}} \cap \gamma(\tilde{U}_{\tilde{x_j}}) \neq \emptyset \tag{2.4}$$

It is clear that this gives us a finite set $G_{i,j}$ of elements $\gamma \in \Gamma/\Gamma_{x_j}$. We have a little lemma

Lemma 2.1.1. *The images $\pi(\tilde{U}_{\tilde{x_i}} \cap \gamma(\tilde{U}_{\tilde{x_j}}))$ are the connected components of $U_{x_i} \cap U_{x_j}$, two elements γ, γ_1 give the same connected component if and only if $\gamma_1 \in \Gamma_{x_i}\gamma\Gamma_{x_j}$.*

Let $F_{i,j} \subset G_{i,j}$ be a set of representatives for the action of Γ_{x_1} on $G_{i,j}$ this set can be identified to the set of connected components. Of course the set $\tilde{U}_{\tilde{x_i}} \cap \gamma(\tilde{U}_{\tilde{x_j}})$ may have a non trivial stabilizer $\Gamma_{i,j,\gamma}$ and then we get an identification

$$\oplus_{\gamma \in F_{i,j}} ev_{\tilde{U}_{x_i} \cap \gamma\tilde{U}_{x_j}} : \tilde{\mathcal{M}}(U_{x_i} \cap U_{x_j}) \xrightarrow{\sim} \bigoplus_{\gamma \in F_{i,j}} \mathcal{M}^{\Gamma_{i,j,\gamma}} \tag{2.5}$$

This is now an explicit (i.e. digestible for a computer) description of the second term in our complex above. We still need to give the explicit formula for d_0 in the complex

$$0 \to \bigoplus_{i \in I} \mathcal{M}^{\Gamma_{\tilde{x}_i}} \xrightarrow{d_0} \bigoplus_{i<j} \bigoplus_{\gamma \in F_{i,j}} \mathcal{M}^{\Gamma_{i,j,\gamma}} \tag{2.6}$$

Looking at the definition it is clear that this map is given by

$$(\ldots, m_i, \ldots, m_j, \ldots) \mapsto (\ldots, m_i - \gamma m_j, \ldots) \tag{2.7}$$

Here we have to observe that $\gamma \in \Gamma/\Gamma_{x_j}$ but this does not matter since $m_j \in \mathcal{M}^{\Gamma_{\tilde{x}_j}}$. So we have an explicit description of the beginning of the Cech complex.

A little reasoning shows of course that a different choice $F'_{i,j}$ of the representatives provides an isomorphic complex.

Now it is clear, how to proceed. At first we have to understand the combinatorics of the covering $\mathfrak{U} = \{U_{x_i}\}_{i\in I}$.

We consider sets

$$G_{\underline{i}} = \{\underline{\gamma} = (e,\gamma_1,\dots,\gamma_q) | \gamma_i \in \Gamma/\Gamma_{x_i}; \tilde{U}_{\tilde{x}_0} \cap \dots \cap \gamma_i \tilde{U}_{\tilde{x_i}} \cap \gamma_q \tilde{U}_{\tilde{x}_q} \neq \emptyset\}$$

on these sets we have an action of Γ_{x_0} by multiplication from the left. Again let $F_{\underline{i}}$ be a system of representatives modulo the action of Γ_{x_0}.

We abbreviate

$$\tilde{U}_{\underline{i},\underline{\gamma}} = \tilde{U}_{\tilde{x}_0} \cap \dots \cap \gamma_i \tilde{U}_{\tilde{x_i}} \cap \gamma_q \tilde{U}_{\tilde{x}_q},$$

let $\Gamma_{\underline{i},\underline{\gamma}}$ be the stabilizer of $\tilde{U}_{\underline{i},\underline{\gamma}}$.

The images $\pi(\tilde{U}_{\underline{i},\underline{\gamma}})$ under the projection map π are the connected components $\pi(\tilde{U}_{\underline{i},\underline{\gamma}}) = U_{\underline{i},\underline{\gamma}} \subset U_{\underline{i}} = U_{x_{i_0}} \cap \dots \cap U_{x_{i_\nu}} \cap \dots U_{x_{i_q}}$. On the other hand each set $\tilde{U}_{\underline{i},\underline{\gamma}}$ is a connected component in $\pi^{-1}(U_{\underline{i},\underline{\gamma}})$. We get an isomorphism

$$\bigoplus_{\underline{\gamma}\in F_{\underline{i}}} ev_{\tilde{U}_{\underline{i},\gamma}} : \tilde{\mathcal{M}}(U_{\underline{i}}) = \tilde{\mathcal{M}}(U_{x_{i_0}} \cap \dots \cap U_{x_{i_\nu}} \cap \dots U_{x_{i_q}}) \xrightarrow{\sim} \bigoplus_{\underline{\gamma}\in F_{\underline{i}}} \mathcal{M}^{\Gamma_{\underline{i},\underline{\gamma}}}. \quad (2.8)$$

We need to give explicit formulas for the boundary maps

$$\bigoplus_{\underline{i}\in I^q} \tilde{\mathcal{M}}(U_{\underline{i}}) \xrightarrow{d_q} \bigoplus_{\underline{i}\in I^{q+1}} \tilde{\mathcal{M}}(U_{\underline{i}}).$$

Abstractly this boundary operator is defined as follows: We look at pairs $\underline{i} \in I^{q+1}, \underline{i}^{(\nu)} \in I^q$ where $\underline{i}^{(\nu)}$ is obtained from $\underline{i}$ by deleting the ν-th entry. Then we have $U_{\underline{i}} \subset U_{\underline{i}^{(\nu)}}$ and from this we get the resulting restriction homomorphism $R_{\underline{i}^{(\nu)},\underline{i}} : \tilde{\mathcal{M}}(U_{\underline{i}^{(\nu)}}) \to \tilde{\mathcal{M}}(U_{\underline{i}})$. Then

$$d_q = \sum_{\underline{i}} \sum_{\nu=0}^{q} (-1)^\nu R_{\underline{i}^{(\nu)},\underline{i}}$$

and hence we have to give an explicit description of $R_{\underline{i}^{(\nu)},\underline{i}}$ with respect to the isomorphism in the diagram (2.8).

We pick two connected components $\pi(\tilde{U}_{\underline{i},\underline{\gamma}}) \subset U_{\underline{i}}$ and $\pi(\tilde{U}_{\underline{i}^{(\nu)},\underline{\gamma}'} \subset U_{\underline{i}^{(\nu)}}$, then we know that

$$\tilde{U}_{\underline{i},\underline{\gamma}} \subset \tilde{U}_{\underline{i}^{(\nu)},\underline{\gamma}'} \iff \exists\, \eta_{\gamma,\gamma'} \in \Gamma \text{ such that } \eta_{\gamma,\gamma'}\gamma'_\mu = \gamma_\mu \text{ for all } \mu \neq \nu$$

and then the restriction of $R_{\underline{i}^{(\nu)},\underline{i}}$ to these two components is given by

$$\begin{array}{ccc} \tilde{\mathcal{M}}(\pi(\tilde{U}_{\underline{i}^{(\nu)},\underline{\gamma}'})) & \xrightarrow{ev_{\tilde{U}_{\underline{i}^{(\nu)},\underline{\gamma}'}}} & \mathcal{M}^{\Gamma_{\underline{i}^{(\nu)},\underline{\gamma}'}} \\ \downarrow R_{\underline{i}^{(\nu)},\underline{i}} & & \downarrow\ \eta_{\gamma,\gamma'} \\ \tilde{\mathcal{M}}(\pi(\tilde{U}_{\underline{i},\underline{\gamma}})) & \xrightarrow{ev_{\tilde{U}_{\underline{i},\underline{\gamma}}}} & \mathcal{M}^{\Gamma_{\underline{i},\underline{\gamma}}} \end{array} \quad (2.9)$$

Here the two horizontal maps are isomorphisms, we observe that $\eta_{\gamma,\gamma'}$ is unique up to an element in $\Gamma_{\underline{i}^{(\nu)},\underline{\gamma}'}$ and hence the vertical arrow $\eta_{\gamma,\gamma'}$ is well defined.

Now we can write down the complex explicitly.

We will show that it follows from reduction theory that

Theorem 2.1.1. *We can construct a finite covering* $\Gamma\backslash X = \cup_{i\in E} U_{x_i} = \mathfrak{U}$ *by orbiconvex sets.*

This of course implies the following theorem of Raghunathan

Theorem 2.1.2. *If R is any commutative ring with identity and if $\mathcal{M}$ is a finitely generated $R-\Gamma-$ module then the total cohomology*

$$\bigoplus_{q\in\mathbb{N}} H^q(\Gamma\backslash X, sh_\Gamma(\mathcal{M}))$$

is a finitely generated R-module

2.1.3 Special examples in low dimensions.

We consider the group $\Gamma = \mathrm{Sl}_2(\mathbb{Z})/\{\pm\mathrm{Id}\}$ and its action on the upper half plane $\mathbb{H}$. We want to investigate the cohomology groups $H^i(\Gamma\backslash H, \tilde{\mathcal{M}})$ for any module Γ-module $\mathcal{M}$. The special points i and ρ in $\Gamma\backslash\mathbb{H}$ are the only points which are fixed points. We construct two nice orbiconvex neighborhoods of these two points, which will cover $\Gamma\backslash\mathbb{H}$. We drop the notation with the tilde and consider i, ρ as points in the upper half plane and as points on $\Gamma\backslash\mathbb{H}$. The stabilizers Γ_i, resp. Γ_ρ are cyclic and generated by the two elements

$$S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, R = \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix} \qquad (RS)$$

respectively.

Now we consider i. In the fundamental domain we consider a strip $V_i = \{z \mid -1/2+\epsilon \le \Re(z) \le 1/2-\epsilon\}$. To this strip we apply the matrix $\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$, we take the union $V_i \cup \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} V_i$ and we get our orbiconvex neighborhood U_i of i. Let us look at ρ. In the fundament domain $\mathcal{F}$ we consider the subset $V_\rho^- = \{z \in \mathcal{F} | \epsilon \le \Re(z) \le 1/2\}$ We should also consider we consider the corresponding subset V_ρ^+ containing ρ^2, (Here we have an ambiguity, we have two points in the fundamental domain lying over the fixed point ρ.) we translate this set by the translation by one, then we get the the set $V_\rho = V_\rho^- \cup (V_\rho^+ + 1)$. To this set we apply the elements the stabiliser and the union of the images under the action of the stabiliser of ρ we get a nice orbiconvex neighborhood U_ρ. If we take our $\epsilon > 0$ small enough then clearly

$$\Gamma\backslash\mathbb{H} = U_i \cup U_\rho \qquad (Cov)$$

and we get a resolution of a sheaf $\mathrm{sh}_\Gamma(\mathcal{M}) = \tilde{\mathcal{M}}$

$$0 \to \tilde{\mathcal{M}} \to \tilde{\mathcal{M}}_i \times \tilde{\mathcal{M}}_\rho \to \tilde{\mathcal{M}}_{i,\rho} \to 0$$

and hence the cohomology groups are given by the cohomology of the complex

$$0 \to \mathcal{M}^{\Gamma_i} \oplus \mathcal{M}^{\Gamma_\rho} \to \mathcal{M} \to 0.$$

Then $H^0(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) = \mathcal{M}^\Gamma = \mathcal{M}^{\Gamma_i}\cap\mathcal{M}^{\Gamma_\rho}$. Since this is true for any Γ module we easily conclude that Γ is generated by Γ_i,Γ_ρ.

We get

$$H^1(\mathrm{Sl}_2(\mathbb{Z})\backslash\mathbb{H},\tilde{\mathcal{M}}_{\mathbb{Z}}) = \mathcal{M}/(\mathcal{M}^{(<S>}\oplus\mathcal{M}^{<R>}), \tag{2.10}$$

and the cohomology vanishes in higher degrees.

Exercise 1: *Let $\Gamma'\subset\Gamma=\mathrm{Sl}_2(\mathbb{Z})/\pm\mathrm{Id}$ be a subgroup of finite index. Prove*

ii) We have (Shapiros lemma)

$$H^1(\Gamma'\backslash\mathbb{H},\mathbb{Z}) = H^1\Gamma\backslash\mathbb{H},\ \widetilde{\mathrm{Ind}_{\Gamma'}^{\Gamma}\mathbb{Z}}).$$

These cohomology groups are free of rank

$$[\Gamma:\Gamma'] - n_i - n_\rho + 1$$

where n_i (resp. n_ρ) is the number of orbits of Γ_i (resp. Γ_ρ) on $\Gamma'\backslash\Gamma$. If Γ' is torsion free then

$$\mathrm{rank}(H^1\Gamma\backslash\mathbb{H},\ \widetilde{\mathrm{Ind}_{\Gamma'}^{\Gamma}\mathbb{Z}}) = \frac{1}{6}[\Gamma:\Gamma']+1$$

The Euler-characteristic of $\Gamma'\backslash\mathbb{H}$ is $\frac{1}{6}[\Gamma:\Gamma']$.

Exercise 2: *Let $\mathcal{M}_n$ be the module of homogenous polynomials in the two variables X,Y and coefficients in $\mathbb{Z}$. We have an action of $\Gamma=\mathrm{Sl}_2(\mathbb{Z})$ on this module by*

$$\begin{pmatrix} a & b \\ c & d\end{pmatrix} P(X,Y) = P(aX+cY, bX+dY).$$

these modules define a sheaf $\tilde{\mathcal{M}}_n$ on $\Gamma\backslash\mathbb{H}$, and we want to investigate their cohomology groups.

Prove:

i) If n is odd, then $\mathcal{M}_n = 0$.

Hence we assume $n\geq 2$ and n even from now on.

ii) $H^0(\Gamma\backslash\mathbb{H},\mathcal{M}_n)=0$.

iii) If we tensorize by $\mathbb{Q}$, then $H^1(\Gamma\backslash\mathbb{H},\mathcal{M}_n\otimes\mathbb{Q})$ is a vector space of rank $n-1-2\left[\frac{n}{4}\right]-2\left[\frac{n}{6}\right]$.

Hint: *Diagonalize the action of Γ_i and Γ_ρ on $\mathcal{M}_n\otimes\overline{\mathbb{Q}}$ separately and look at the eigenspaces. To say it differently: Over $\bar{\mathbb{Q}}$ we can conjugate the matrices $\begin{pmatrix} 0 & -1 \\ 1 & 0\end{pmatrix}$, $\begin{pmatrix} 1 & 1 \\ -1 & 0\end{pmatrix}$ into the diagonal maximal torus $\begin{pmatrix} t & 0 \\ 0 & t^{-1}\end{pmatrix}$, and then look at the decomposition of $\mathcal{M}_n$ into weight spaces.*

iv) Investigate the torsion in $H^1(\Gamma\backslash\mathbb{H},\mathcal{M}_n)$. (Start from the sequence $0\to\mathcal{M}_n\to\mathcal{M}_n\to\mathcal{M}_n/\ell\mathcal{M}_n\to 0$.)

v) Now we consider $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$. *The two matrices* $S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ *and* $R = \begin{pmatrix} 1 & 1 \\ -1 & 0 \end{pmatrix}$ *are generators of the stabilisers of* i *and* ρ *respectively.*

We take for our module M *the cyclic group* $\mathbb{Z}/12\mathbb{Z}$,*consider the spectral sequence*

$$H^p(\Gamma\backslash\mathbb{H}, R^q(\mathrm{sh}_\Gamma)(\mathbb{Z}/12\mathbb{Z}).$$

Show that $H^0(\Gamma\backslash\mathbb{H}, R^1(\mathrm{sh}_\Gamma)(\mathbb{Z}/12\mathbb{Z}) = \mathbb{Z}/12\mathbb{Z}$. *Show that the differential*

$$H^0(\Gamma\backslash\mathbb{H}, R^1(\mathrm{sh}_\Gamma)(\mathbb{Z}/12\mathbb{Z}) \to H^2(\Gamma\backslash\mathbb{H}, \mathrm{sh}_\Gamma(\mathbb{Z}/12\mathbb{Z})$$

vanishes and conclude

$$H^1(\Gamma, \mathbb{Z}/12\mathbb{Z}) = \mathbb{Z}/12\mathbb{Z}.$$

The group $\Gamma = \mathbf{Sl}_2(\mathbb{Z}[i])$

A similar computation can be made up to compute the cohomology in the case of $\tilde{\Gamma} = \mathrm{Gl}_2(\mathcal{O})$. We have the three special points x_{12}, x_{13} and x_{23} (See(1.2.1), and we choose closed sets A_{ij} containing these points which just leave out a small open strip containing the opposite face. If $\tilde{A}_{ij}$ is a component of the inverse image of A_{ij} in $\mathbb{H}_3$, then

$$A_{ij} = \Gamma_{ij}\backslash\tilde{A}_{ij}.$$

The intersections $A_{ij} \cap A_{i'j'} = A_\nu$ are closed sets. They are of the form

$$A_\nu = \Gamma_\nu\backslash\tilde{A}_\nu$$

where Γ_ν is the stabilizer of the arc joining x_{ij} and $x_{i'j'}$. The restrictions of our sheaves $\tilde{\mathcal{M}}$ to the A_{ij} and A_ν and to $A = A_{12} \cap A_{23} \cap A_{13}$ are acyclic and hence we get a complex

$$0 \longrightarrow \tilde{\mathcal{M}} \longrightarrow \bigoplus_{(i,j)} \tilde{\mathcal{M}}_{A_{ij}} \longrightarrow \bigoplus \tilde{\mathcal{M}}_{A_\nu} \longrightarrow \tilde{\mathcal{M}}_A \longrightarrow 0$$

where the $\tilde{\mathcal{M}}_?$ are the restrictions of $\tilde{\mathcal{M}}$ to ??? and then extended to the space again.

Hence we find that our cohomology groups are equal to the cohomology groups of the complex

$$0 \longrightarrow \bigoplus_{(i,j)} \mathcal{M}^{\Gamma_{ij}} \xrightarrow{d^1} \bigoplus_{\nu} \mathcal{M}^{\Gamma_\nu} \xrightarrow{d^2} \mathcal{M} \longrightarrow 0$$

with boundary maps

$$d^1 : (m_{12}, m_{13}, m_{23}) \longmapsto (m_{12} - m_{13}, m_{23} - m_{12}, m_{13} - m_{23})$$
$$d^2 : (m_1, m_2, m_3) \longmapsto m_1 + m_2 + m_3.$$

If we take for instance $\tilde{\mathcal{M}} = \mathbb{Z}$ then we get $H^0(\tilde{\Gamma}\backslash\mathbb{H}_3, \mathbb{Z}) = \mathbb{Z}$ and $H^i(\tilde{\Gamma}\backslash\mathbb{H}_3, \mathbb{Z}) = 0$ for $i > 0$ as it should be.

Homology, Cohomology with compact support and Poincaré duality.

Here we have to use the theory of compactifications. For any locally symmetric space we can embed $\Gamma\backslash X$ into its Borel-Serre compactification

$$i : \Gamma\backslash X \longrightarrow \Gamma\backslash\overline{X}_{BS},$$

and this process was explained in detail for our low dimensional examples. Especially we give an explicit description of a neighborhood of a point $x \in \partial(\Gamma\backslash\overline{X}_{BS})$. If we have a sheaf $\tilde{\mathcal{M}}$ on $\Gamma\backslash X$, we can extend it to the compactification by using the functor i_*. We get a sheaf

$$i_*(\tilde{\mathcal{M}}) \quad \text{on} \quad \Gamma\backslash\overline{X}_{BS},$$

it is clear from the description of a neighborhood of a point in the boundary, that i_* is exact. (This is not true for the Baily-Borel compactification.)

Our construction $\mathcal{M} \to \tilde{\mathcal{M}}$ can be extended to the action of Γ on $\overline{X}_{BS}$ and clearly

$$i_*(\tilde{\mathcal{M}}) = \text{ result of the construction } \mathcal{M} \to \tilde{\mathcal{M}} \text{ on } \Gamma\backslash\overline{X}_{BS}.$$

Hence we get from our general results in Chapter I, ... that

$$H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}}) = H^\bullet(\Gamma\backslash\overline{X}_{BS}, i_*(\tilde{\mathcal{M}})).$$

But we have another construction of extending the sheaf $\tilde{\mathcal{M}}$ from $\Gamma\backslash X$ to $\Gamma\backslash\overline{X}_{BS}$. This is the so called extension by zero. We define the sheaf $i_!(\tilde{\mathcal{M}})$ on $\Gamma\backslash\overline{X}_{BS}$ by giving the stalks. For $x \in \Gamma\backslash\overline{X}_{BS}$ we put

$$i_!(\tilde{\mathcal{M}})_x = \begin{cases} \tilde{\mathcal{M}}_x & \text{if} \quad x \in \Gamma\backslash X \\ 0 & \text{if} \quad x \notin \Gamma\backslash X \end{cases}.$$

It is clear that $i_!$ is an exact functor sending sheaves on $\Gamma\backslash X$ to sheaves on $\Gamma\backslash\overline{X}_{BS}$, and we have for an arbitrary sheaf

$$H^0(\Gamma\backslash\overline{X}_{BS}, i_!(\mathcal{F})) = H^0_c(\Gamma\backslash X, \mathcal{F})$$

where $H^0_c(\Gamma\backslash X, \mathcal{F})$ is the abelian group of those sections $s \in H^0(\Gamma\backslash X, \mathcal{F})$ for which the support

$$\text{supp } (s) = \{x \mid s_x \neq 0\}$$

is compact.

Hence we define the cohomology with compact supports as

$$H^q_c(\Gamma\backslash X, \mathcal{F}) = H^q(\Gamma\backslash\overline{X}_{BS}, i_!\mathcal{F})).$$

If $\tilde{\mathcal{M}}$ is a sheaf on $\Gamma\backslash X$ which is obtained from a Γ-module $\mathcal{M}$, then it is quite clear that

$$H^0_c(\Gamma\backslash X, \tilde{\mathcal{M}}) = 0,$$

provided our quotient $\Gamma\backslash X$ is not compact.

The cohomology with compact supports is actually related to the homology of the group: I want to indicate that we have a natural isomorphism

$$H_i(\Gamma, \mathcal{M}) \simeq H_c^{d-i}(\Gamma\backslash X, \tilde{\mathcal{M}})$$

under the assumption that X is connected and the orders of the stabilizers are invertible in R.

This is the analogous statement to the theorem .... which we discussed when we introduced cohomology.

Our starting point is the fact that the projective Γ-modules have analogous vanishing properties as the induced modules.

Lemma: *Let us assume that Γ acts on the connected symmetric space X. If P if a projective module then*

$$H_c^i(\Gamma\backslash X, \tilde{P}) = \begin{cases} 0 & \textit{if} \quad i \neq \dim X \\ & \\ P_\Gamma & \textit{if} \quad i = \dim X. \end{cases}$$

Let us believe this lemma. Then it is quite clear that

$$H_i(\Gamma, \mathcal{M}) \simeq H_c^{d-i}(\Gamma\backslash X, \tilde{P}),$$

because both sides can be computed from a projective resolution.

2.1.3 The homology as singular homology

We have still another description of the homology. We form the singular chain complex

$$\to C_i(X) \to C_{i-1}(X) \to \ldots \to C_0(X) \to 0.$$

This is a complex of Γ-modules, and we can form the tensor product with $\mathcal{M}$. We get a complex of Γ-modules

$$\longrightarrow C_i(X) \otimes \mathcal{M} \longrightarrow C_{i-1}(X) \otimes \mathcal{M} \longrightarrow \ldots.$$

We define the chain complex

$$C_\bullet(\Gamma\backslash X, \underline{\mathcal{M}}),$$

simply a resulting complex if we take the Γ-coinvariants.

But we may choose for our module $\mathcal{M}$ simply the group ring. Then we have clearly

$$(C_\bullet(X) \otimes \mathbb{Z}[\Gamma])_\Gamma \simeq C_\bullet(X),$$

and hence we have, since X is a cell, that

$$H_i(\Gamma\backslash X, \underline{\mathbb{Z}[\Gamma]}) = 0 \qquad \text{for} \qquad i > 0.$$

On the other hand we have

$$H_0(\Gamma\backslash X, \underline{\mathcal{M}}) = \mathcal{M}_\Gamma.$$

This follows directly from looking at the complex

$$(C_1(X)\otimes\mathcal{M})_\Gamma \longrightarrow (C_0(X)\otimes\mathcal{M})_\Gamma.$$

First of all we observe that 0-cycles

$$x_1\otimes m - x_0\otimes m$$

are boundaries since X is pathwise connected. On the other hand we have that

$$x_0\otimes m - \gamma x_0\otimes\gamma m \in C_0(X)\otimes\mathcal{M}$$

becomes zero if we go to the coinvatiants and this implies the assertion.

If we have in addition that the orders of the stabilizers are invertible in R than it is clear that a short exact sequence of R-Γ-modules

$$0\longrightarrow\mathcal{M}'\longrightarrow\mathcal{M}\longrightarrow\mathcal{M}''\longrightarrow 0$$

leads to an exact sequence of complexes

$$0\longrightarrow C_\bullet(\Gamma\backslash X,\underline{\mathcal{M}}')\longrightarrow C_\bullet(\Gamma\backslash X,\underline{\mathcal{M}})\longrightarrow C_\bullet(\Gamma\backslash X,\underline{\mathcal{M}}'')\longrightarrow 0,$$

and hence to a long exact cohomology sequence

$$H_i(\Gamma\backslash X,\underline{\mathcal{M}}')\longrightarrow H_i(\Gamma\backslash X,\underline{\mathcal{M}})\longrightarrow H_i(\Gamma\backslash X,\underline{\mathcal{M}}'')\longrightarrow H_{i-1}(\Gamma\backslash X,\underline{\mathcal{M}}').$$

Now it is clear that

$$H_i(\Gamma,\mathcal{M})\simeq H_i(\Gamma\backslash X,\underline{\mathcal{M}})\simeq H_c^{d-i}(\Gamma\backslash X,\tilde{\mathcal{M}}).$$

The fundamental exact sequence

By construction we have the exact sequence

$$0\to i_!(\tilde{\mathcal{M}})\to i_*(\tilde{\mathcal{M}})\to i_*(\tilde{\mathcal{M}})/i_!(\tilde{\mathcal{M}})\to 0$$

of sheaves and clearly $i_*(\mathcal{M})/i_!(\mathcal{M})$ is simply the restriction of $i_*(\tilde{\mathcal{M}})$ to the boundary extended by zero to the entire space. This yields the *fundamental exact sequence*

$$\to H^{q-1}(\partial(\Gamma\backslash X),\tilde{\mathcal{M}})\to H_c^q(\Gamma\backslash X,\tilde{\mathcal{M}})\to H^q(\Gamma\backslash\bar{X},\tilde{\mathcal{M}})\to H^q(\partial(\Gamma\backslash X),\tilde{\mathcal{M}})\to\dots$$

We define the "inner cohomology" $H_!^q(\Gamma\backslash X,\tilde{\mathcal{M}})$ as the image of $H_c^q(\Gamma\backslash X,\tilde{\mathcal{M}})\to H^q(\Gamma\backslash X,\tilde{\mathcal{M}})$. (This a little bit misleading because these groups are not honest cohomology groups. An exact sequence of sheaves $0\to\mathcal{M}'\to\mathcal{M}\to\mathcal{M}''\to 0$ does not provide an exact sequence for the $H_!$ groups.)

We want to have a slightly different look at this sequence. We recall the covering (See 1.59,1.60)

$$\Gamma\backslash X=\Gamma\backslash X(r)\cup\overset{\bullet}{\mathcal{N}}(\Gamma\backslash X)=\Gamma\backslash X(r)\cup\bigcup_{P:P\text{proper}}\Gamma_P\backslash X^P(\underline{c}_{\pi'},r(\underline{c}_{\pi'}))\quad(2.11)$$

where the union runs over Γ conjugacy classes of parabolic subgroups over $\mathbb{Q}$ and $\overset{\bullet}{\mathcal{N}}(\Gamma\backslash X)$ is a punctured tubular neighborhood of ∞, i.e. the boundary of the Borel-Serre compactification.

It is well known (See for instance [book] vol I , 4.5) that from a covering $\Gamma\backslash X = \bigcup_i V_i$ we get a Čzech complex and a spectral sequence with $E_1^{p,q}$- term

$$\prod_{\underline{i}=\{i_0,i_1\dots,i_p\}} H^q(V_{\underline{i}},\tilde{\mathcal{M}}) \tag{2.12}$$

where $V_{\underline{i}} = V_{i_0}\cap\dots\cap V_{i_p}$. The boundary in the Čzech complex gives us the differential

$$d_1^{p,q}: \prod_{\underline{i}=\{i_0,i_1\dots,i_p\}} H^q(V_{\underline{i}},\tilde{\mathcal{M}}) \to \prod_{\underline{j}=\{j_0,j_1\dots,j_{p+1}\}} H^q(V_{\underline{j}},\tilde{\mathcal{M}}) \tag{2.13}$$

Here we work with the alternating Čzech complex, we also assume that we have an ordering on the set of simple positive roots. If such a $V_{\underline{i}}$ is non empty then it of the form $\Gamma_Q\backslash X^Q(C(\underline{\tilde{c}}))$.

We return to the diagram (1.64), on the left hand side we can divide by Γ_Q. We have the map which maps a Cartan involution on X to a Cartan-involution on M. Then we get a diagram

$$\begin{array}{ccc} f^\dagger: X^Q(C(\underline{\tilde{c}})) & \to & X^M(r)\times C_{U_Q}(\underline{\tilde{c}}) \\ \downarrow p_Q & & \downarrow p_M \\ f:\Gamma_Q\backslash X^Q(C(\underline{\tilde{c}})) & \to & \Gamma_M\backslash X^M(r)\times C_{U_Q}(\underline{\tilde{c}})) \end{array} \tag{2.14}$$

where the bottom line is a fibration. To describe the fiber in a point $\tilde{x}$ we pick a point $x\in(p_m\circ f^\dagger)^{-1}$. Then $U_Q(\mathbb{R})$ acts simply transitively on the fiber $(f^\dagger)^{-1}(f^\dagger(x))$ hence $U_Q(\mathbb{R}) = (f^\dagger)^{-1}(f^\dagger(x))$. Then $p_Q: U_Q(\mathbb{R})\to\Gamma_{U_Q}\backslash U_Q(\mathbb{R})$ yields the identification $i_x:\Gamma_{U_Q}\backslash U_Q(\mathbb{R})\xrightarrow{\sim} f^{-1}(\tilde{x})$. If we replace x by $\gamma x = x_1$ with $\gamma\in\Gamma_{U_Q}$ then we get $i_{x_1} = \mathrm{Ad}(\gamma)\circ i_x$ where for $u\in U_{U_Q}$ $\mathrm{Ad}(\gamma)(u) = \gamma u\gamma^{-1}$ where for $u\in U_Q(\mathbb{R})$, under this action of Γ_Q.

We have the spectral sequence

$$H^p(\Gamma_M\backslash X^M(r), R^q f_*(\tilde{\mathcal{M}}))\Rightarrow H^{p+q}(\Gamma_Q\backslash X^Q(C(\underline{c}_{\pi_1},\dots,c_{\pi_\nu})),\tilde{\mathcal{M}})$$

and clearly $R^q f_*(\tilde{\mathcal{M}})$ is a locally constant sheaf. This sheaf is easy to determine. Under the above identification we get an isomorphism

$$i_x^\bullet: H^\bullet(\Gamma_{U_Q}\backslash U_Q(\mathbb{R}),\tilde{\mathcal{M}}))\xrightarrow{\sim} R^\bullet(\tilde{\mathcal{M}})_{\tilde{x}}.$$

The adjoint action $\mathrm{Ad}:\Gamma_Q\to\mathrm{Aut}(\Gamma_{U_Q}\backslash U_Q(\mathbb{R}))$ induces an action of Γ_Q on the cohomology $H^\bullet((\Gamma_{U_Q}\backslash U_Q(\mathbb{R})),\tilde{\mathcal{M}})$. Since the functor cohomology is the derived functor of taking Γ_{U_Q} invariants it follows that the restriction of Ad to Γ_{U_Q} acts trivially on $H^\bullet(\Gamma_{U_Q}\backslash U_Q(\mathbb{R}),\tilde{\mathcal{M}})$. Consequently $H^\bullet((\Gamma_{U_Q}\backslash U_Q(\mathbb{R})),\tilde{\mathcal{M}})$ is a Γ_M- module. We get

$$R^\bullet f_*(\tilde{\mathcal{M}})\xrightarrow{\sim} H^\bullet(\Gamma_{U_Q}\widetilde{\backslash U_Q(\mathbb{R}),\tilde{\mathcal{M}}})$$

and our spectral sequence becomes

$$H^p(\Gamma_M\backslash X^M(r), H^\bullet(\widetilde{(\Gamma_{U_Q}\backslash U_Q(\mathbb{R}))}, \tilde{\mathcal{M}})) \Rightarrow H^{p+q}(\Gamma_Q\backslash X^Q(C(\underline{\tilde{c}})), \tilde{\mathcal{M}})$$

We can take the composition $r_Q \circ f$. Then it is obvious that for any point $c_0 \in C_{U_Q}(\underline{\tilde{c}}))$ the restriction map

$$H^\bullet(X^Q(C(\underline{\tilde{c}})), \tilde{\mathcal{M}}) \to H^\bullet(X^Q((r_Q \circ f)^{-1}(c_0), \tilde{\mathcal{M}}) \tag{2.15}$$

is an isomorphism. On the other hand it is clear that we may vary our parameter $\underline{\tilde{c}}$ we may assume that the $C_{U_Q}(\underline{\tilde{c}})$ go to infinity. Then we may enlarge the parameter r without violating the assumptions in proposition 1.2.3. Hence we get that the inclusion $\Gamma_Q\backslash X^Q(C(\underline{\tilde{c}})) \subset \Gamma_Q\backslash X^Q$ induces an isomorphism in cohomology

$$H^\bullet(\Gamma_Q\backslash X^Q(C(\underline{\tilde{c}})), \tilde{\mathcal{M}}) \xrightarrow{\sim} H^\bullet(\Gamma_Q\backslash X, \tilde{\mathcal{M}}) \tag{2.16}$$

We choose a total ordering on the set of Γ conjugacy classes of parabolic subgroups, i.e. we enumerate them by a finite interval of integers $[1, N]$. We also enumerate the set of simple roots $\{\alpha_1, \dots, \alpha_d\}$ in our special case $\alpha_i = \alpha_{i,i+1}$. For any conjugacy class $[P]$ we define the type of P to be $t(P) = \pi^{U_P}$ the subset of unipotent simple roots and $d(P) = \#\pi^{U_P}$ the cardinality of this set. If $P_{i_1}, \dots, P_{i_r}$ are maximal, $i_1 < i_2 \dots < i_r$ and if $P_{i_1}\cap, \dots \cap P_{i_r} = Q$ is a parabolic subgroup then we require that $t(P_{i_1}) < \dots < t(P_{i_r})$.

The indexing set $\mathrm{Par}(\Gamma)$ of our covering is the Γ conjugacy classes of parabolic subgroups over $\mathbb{Q}$. If we have a finite set $[P_{i_0}], [P_{i_1}], \dots, [P_{i_p}]$ of conjugacy classes then we say $[Q] \in [P_{i_0}], [P_{i_1}], \dots, [P_{i_p}]$ if we can find representatives $P'_{i_\nu} \in [P_{i_\nu}]$ and $Q' \in [Q]$ such that $Q' = P'_{i_0} \cap \dots P'_{i_p}$.

Hence we see that the $E_1^{\bullet,q}$ complex in our spectral sequence (2.13) is given by

$$\prod_i H^q(\Gamma_{Q_i}\backslash X^{Q_i}(C(\underline{\tilde{c}})), \tilde{\mathcal{M}}) \to \prod_{i<j} \prod_{[R]\in[Q_i]\cap[Q_j]} H^q(\Gamma_R\backslash X^R(C(\underline{\tilde{c}})), \tilde{\mathcal{M}}) \to \tag{2.17}$$

this obtained from our covering (1.60). Now we replace our covering by a simplicial space, i.e. we consider the diagram of maps between spaces

$$\mathfrak{Par} := \prod_i \Gamma_{Q_i}\backslash X \overset{p_1}{\underset{p_2}{\leftleftarrows}} \prod_{i<j} \prod_{[R]\in[Q_i]\cap Q_j]} \Gamma_R\backslash X \begin{smallmatrix}\longleftarrow\\ \longleftarrow\\ \longleftarrow\end{smallmatrix} \tag{2.18}$$

this yields a spectral sequence with $E_1^{\bullet,q}$ term

$$\prod_i H^q(\Gamma_{Q_i}\backslash X, \tilde{\mathcal{M}}) \xrightarrow{d^{(0)}} \prod_{i<j} \prod_{[R]\in[P_i]\cap[P_j]} H^q(\Gamma_R\backslash X^R, \tilde{\mathcal{M}}) \xrightarrow{d^{(1)}} \tag{2.19}$$

Our covering also yields a simplicial space which is a subspace of (2.18) we get a map from (2.13) to (2.19) and this map is an isomorphism of complexes.

We replace $\mathfrak{Par}$ by another simplicial complex

$$\mathfrak{Parmax} := \prod_{[P]:d(P)=1} \Gamma_P\backslash X \underset{p_2}{\overset{p_1}{\leftleftarrows}} \prod_{[Q]:d(Q)=2} \Gamma_Q\backslash X \begin{smallmatrix}\longleftarrow\\ \longleftarrow\\ \longleftarrow\end{smallmatrix} \tag{2.20}$$

We have an obvious projection $\Pi : \mathfrak{Par} \to \mathfrak{Parmax}$ which induces a homomorphism

$$\begin{array}{ccccc} \prod_i H^q(\Gamma_{Q_i}\backslash X, \tilde{\mathcal{M}}) & \xrightarrow{d^{(0)}} & \prod_{i<j} \prod_{[R]\in[P_i]\cap[P_j]} H^q(\Gamma_R\backslash X^R, \tilde{\mathcal{M}}) & \xrightarrow{d^{(1)}} \\ \uparrow & & \uparrow & \\ \prod_{[P]:d(P)=1} H^q(\Gamma_P\backslash X, \tilde{\mathcal{M}}) & \xrightarrow{d^{(0)}} & \prod_{[R]:d(R)=2} H^q(\Gamma_R\backslash X^R, \tilde{\mathcal{M}}) & \xrightarrow{d^{(1)}} \end{array} \tag{2.21}$$

and an easy argument in homological algebra shows that this induces an isomorphism in cohomology or in other words an isomorphism of the $E_2^{p,q}$ terms of the two spectral sequences.

We had the covering

$$\overset{\bullet}{\mathcal{N}} (\Gamma\backslash X) = \bigcup_{P:P\text{proper}} \Gamma_P\backslash X^P(\underline{c}_{\pi'}, r(\underline{c}_{\pi'})) \tag{2.22}$$

which gives us the spectral sequence converging to $H^\bullet(\overset{\bullet}{\mathcal{N}} (\Gamma\backslash X), \tilde{\mathcal{M}})$ with

$$E_1^{p,q} = \bigoplus_{i_0<i_1<\cdots<i_p} \bigoplus_{[Q]\in[P_{i_0}]\cap[P_{i_1}]\cap\cdots\cap[P_{i_p}]} H^q(\Gamma_Q\backslash X^Q(\underline{c}_{\pi'}, r(\underline{c}_{\pi'}))) \tag{2.23}$$

Our covering of $\overset{\bullet}{\mathcal{N}} (\Gamma\backslash X)$ gives us a simplicial space $\mathfrak{Cov}(\overset{\bullet}{\mathcal{N}})\Gamma\backslash X)$ and we have maps

$$\mathfrak{Cov}(\overset{\bullet}{\mathcal{N}} (\Gamma\backslash X)) \hookrightarrow \mathfrak{Par} \to \mathfrak{Parmax}. \tag{2.24}$$

We saw that the resulting maps induced an isomorphism in the $E_2^{p,q}$ terms of the spectral sequences. Hence we see that $\mathfrak{Parmax}$ yields a spectral sequence

$$E_1^{p,q} = \bigoplus_{[P]:d(P)=p+1} H^q(\Gamma_P\backslash X, \tilde{\mathcal{M}}) \Rightarrow H^{p+q}(\overset{\bullet}{\mathcal{N}} (\Gamma\backslash X), \tilde{\mathcal{M}})) \tag{2.25}$$

At this point we want to raise an interesting question

Does this spectral sequence degenerate at $E_2^{p,q}$ level?

The author of this book is hoping that the answer to this question is no! And this is so for interesting reasons! We come back to this question when we discuss the Eisenstein cohomology.

The complement of $\overset{\bullet}{\mathcal{N}}(\Gamma\backslash X)$ is a relatively compact open set $V \subset \Gamma\backslash X$, this set contains the stable points. We define $\tilde{\mathcal{M}}^!_V = i_{V,!}(\tilde{\mathcal{M}})$ then we get an exact sequence

$$0 \to \tilde{\mathcal{M}}^!_V \to \tilde{\mathcal{M}} \to \tilde{\mathcal{M}}/\tilde{\mathcal{M}}^!_V \to 0 \tag{2.26}$$

and $\tilde{\mathcal{M}}/\tilde{\mathcal{M}}^!_V$ is obviously the extension of the restriction of $\tilde{\mathcal{M}}$ to $\overset{\bullet}{\mathcal{N}}(\Gamma\backslash X)$ and the extended by zero to $\Gamma\backslash X$. We claim (easy proof later) that

$$H^\bullet_c(\Gamma\backslash X, \tilde{\mathcal{M}}) = H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}}^!_V) \tag{2.27}$$

and this gives us again the fundamental exact sequence

$$H^{q-1}(\overset{\bullet}{\mathcal{N}}(\Gamma\backslash X), \tilde{\mathcal{M}}) \to H^q(\Gamma\backslash X, \tilde{\mathcal{M}}^!_V) \to H^q(\Gamma\backslash X, \tilde{\mathcal{M}}) \to H^q(\overset{\bullet}{\mathcal{N}}(\Gamma\backslash X), \tilde{\mathcal{M}}) \to \tag{2.28}$$

How to compute the cohomology groups $H^q_c(\Gamma\backslash X, \tilde{\mathcal{M}})$

We apply the considerations in 4.8 from the [book]. Again we cover $\Gamma\backslash X$ by orbiconvex open neighborhoods U_{x_i}, and now we define

$$\tilde{\mathcal{M}}^!_{\underline{x}} = (i_{\underline{x}})_! i^*_{\underline{x}}(\tilde{\mathcal{M}}).$$

These sheaves have properties, which are dual to those of the sheaves $\tilde{\mathcal{M}}_{ulx}$. If $\underline{x} = (x_1, \dots, x_s)$ and if we add another point $\underline{x}' = (x_1, \dots, x_s, x_{s+1})$ then we have the restriction $\tilde{\mathcal{M}}_{\underline{x}} \to \tilde{\mathcal{M}}_{\underline{x}'}$, which were used to construct the Čech resolution.

Now let $d = \dim(X)$. For the ! sheaves we get (See [book] , loc. cit.) get a morphism $\tilde{\mathcal{M}}^!_{\underline{x}'} \to \tilde{\mathcal{M}}^!_{\underline{x}}$. For $\underline{x} = (x_1, \dots, x_s)$ we define the degree $d(\underline{x}) = d+1-s$. Then we construct the Čech-coresolution (See [book], 4.8.3)

$$\to \prod_{\underline{x}:d(\underline{x})=q} \tilde{\mathcal{M}}^!_{\underline{x}} \to \cdots \to \prod_{(x_i,x_j)} \tilde{\mathcal{M}}^!_{x_i,x_j} \to \prod_{x_i} \tilde{\mathcal{M}}^!_{x_i} \to i_!(\tilde{\mathcal{M}}) \to 0.$$

Now we have a dual statement to the proposition with label **acyc**

Proposition: **(acyc!)** *If* $d = \dim(X)$ *then*

$$H^q(U_{\tilde{\underline{x}}}, \tilde{\mathcal{M}}^!_{\underline{x}}) = \begin{cases} \mathcal{M}_{\Gamma_{\tilde{y}}} & q = d \\ 0 & q \neq d \end{cases}$$

Hence the above complex of sheaves provides a complex of modules $C^\bullet_!(\mathfrak{U}, \tilde{\mathcal{M}})$:

$$\to \prod_{\underline{x}:d(\underline{x})=q} H^d(U_{\underline{x}}, \tilde{M}^!_{\underline{x}}) \to \cdots \to \prod_{(x_i,x_j)} H^d(U_{x_i,x_j}, \tilde{\mathcal{M}}^!_{x_i,x_j}) \to \prod_{x_i} \tilde{H}^d(U_{x_i}, \tilde{\mathcal{M}}^!_{x_i}) \to 0.$$

Now it is clear that

$$H^q(\Gamma\backslash X, i_!(\tilde{\mathcal{M}})) = H^q_c(\Gamma\backslash X, \tilde{\mathcal{M}}) = H^q(C^\bullet_!(\mathfrak{U}, \tilde{\mathcal{M}})).$$

Now let us assume that $\mathcal{M}$ is a finitely generated module over some commutative noetherian ring R with identity. Then clearly all our cohomology groups will be R-modules.

Our Theorem A above implies

Theorem (Raghunathan) *Under our general assumptions all the cohomology groups $H^q_c(\Gamma\backslash X, \tilde{\mathcal{M}}), H^q(\Gamma\backslash X, \tilde{\mathcal{M}}), H^q_!(\Gamma\backslash X, \tilde{\mathcal{M}}), H^q(\partial(\Gamma\backslash X), \tilde{\mathcal{M}})$ are finitely generated R modules.*

The case $\Gamma = \mathbf{Sl}_2(\mathbb{Z})$

In the following $\mathcal{M}$ can be any Γ-module. We investigate the fundamental exact sequence for this special group.

Of course we start again from our covering $\Gamma\backslash\mathbb{H} = U_i \cup U_\rho$. The cohomology with compact supports is the cohomology of the complex

$$0 \to H^2(U_i \cap U_\rho, \tilde{\mathcal{M}}^!_{i,\rho}) \to H^2(U_i\ , \tilde{\mathcal{M}}^!_i) \oplus H^2(U_\rho, \tilde{\mathcal{M}}^!_\rho) \to 0.$$

Now we have $H^2(U_i \cap U_\rho, \tilde{\mathcal{M}}^!_{i,\rho}) = M, H^2(U_i\ , \tilde{\mathcal{M}}^!_i) = \mathcal{M}_{\Gamma_i} = \mathcal{M}/(\mathrm{Id} - S)M, H^2(U_\rho\ , \tilde{\mathcal{M}}^!_\rho) = M_{\Gamma_\rho} = \mathcal{M}/(\mathrm{Id} - R)\mathcal{M}$ and hence we get the complex

$$0 \to \mathcal{M} \to \mathcal{M}_{\Gamma_i} \oplus \mathcal{M}_{\Gamma_\rho} \to 0$$

and from this we obtain

$$H^1(\Gamma\backslash\mathbb{H}, i_!(\mathcal{M})) = \ \ker(\mathcal{M} \to (M/(\mathrm{Id} - S)\mathcal{M} \oplus \mathcal{M}/(\mathrm{Id} - R)\mathcal{M}))$$

and

$$H^0(\Gamma\backslash\mathbb{H}, i_!(\mathcal{M})) = 0, H^2(\Gamma\backslash\mathbb{H}, i_!(\mathcal{M})) = \mathcal{M}_\Gamma$$

We discuss the fundamental exact sequence in this special case. To do this we have to understand the cohomology of the boundary $H^\bullet(\partial(\Gamma\backslash\mathbb{H}, \tilde{M})$. We discussed the Borel-Serre compactification and saw that in this case we get this compactification if we add a circle at infinity to our picture of the quotient. But we may as well cut the cylinder at any level $c > 1$, i.e. we consider the level line $\mathbb{H}(c) = \{z = x + ic | z \in \mathbb{H}\}$ and divide this level line by the action of the translation group

$$\Gamma_U = \{\begin{pmatrix} 1 & n \\ 0 & 1 \end{pmatrix} | n \in \mathbb{Z}\} = \{\begin{pmatrix} \epsilon & n \\ 0 & \epsilon \end{pmatrix} | n \in \mathbb{Z}, \epsilon = \pm 1\}/\{\pm \mathrm{Id}\}.$$

But this quotient is homotopy equivalent to the cylinder

$$\Gamma_U\backslash\mathbb{H} \simeq \Gamma_U\backslash\mathbb{H}(c).$$

We apply our general consideration on cohomology of arithmetic groups to this situation and find

$$H^\bullet(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}) = H^\bullet(\Gamma_U\backslash\mathbb{H}, \mathrm{sh}_{\Gamma_U}(\mathcal{M})) = H^\bullet(\Gamma_U\backslash\mathbb{H}(c), \mathrm{sh}_{\Gamma_U}(\mathcal{M})).$$

This cohomology is easy to compute. The group Γ_U is generated by the element $T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$. It is rather clear that

$$H^0(\Gamma_U\backslash\mathbb{H}, \mathrm{sh}_{\Gamma_U}(\mathcal{M})) = \mathcal{M}^{\Gamma_U}, H^1(\Gamma_U\backslash\mathbb{H}, \mathrm{sh}_{\Gamma_U}(\mathcal{M})) = \mathcal{M}_{\Gamma_U} = \mathcal{M}/(\mathrm{Id}-T)\mathcal{M}.$$

Then our fundamental exact sequence becomes (See(2.10)) $\boxed{\text{fundexsq}}$

$$0 \to \mathcal{M}^{\Gamma} \to \mathcal{M}^{\Gamma_U} \to \ \ker(\mathcal{M} \to (\mathcal{M}/(\mathrm{Id}-S)\mathcal{M} \oplus \mathcal{M}/(\mathrm{Id}-R)\mathcal{M})) \xrightarrow{j} \mathcal{M}/(\mathcal{M}^{\Gamma_i} \oplus \mathcal{M}^{\Gamma_\rho}) \xrightarrow{r}$$
$$\mathcal{M}/(\mathrm{Id}-T)\mathcal{M} \to \mathcal{M}_{\Gamma} \to 0 \tag{2.29}$$

Now it may come as a little surprise to the readers, that we can formulate a little exercise which is not entirely trivial

Exercise: *Write down explicitly all the arrows in the above fundamental sequence*

We give the answer without proof. I change notation slightly and work with the matrices
$$S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, R = \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix}$$
and we have the relation
$$RS = T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$$
Then $\Gamma_i =< S >, \Gamma_\rho =< R >$. The map
$$\mathcal{M}/(\mathcal{M}^{<S>} \oplus \mathcal{M}^{<R>}) \to \mathcal{M}/(\mathrm{Id}-T)\mathcal{M}$$
is given by
$$m \mapsto m - Sm$$
We have to show that this map is well defined: If $m \in \mathcal{M}^{<S>}$ then $m \mapsto 0$. If $m \in \mathcal{M}^{<R>}$ then
$$m - Sm = m - SR^{-1}m = m - Tm$$
and this is zero in $\mathcal{M}/(\mathrm{Id}-T)\mathcal{M}$.

The map
$$\ker(\mathcal{M} \to (\mathcal{M}/(\mathrm{Id}-S)\mathcal{M} \oplus \mathcal{M}/(\mathrm{Id}-R)\mathcal{M})) \to \mathcal{M}/(\mathcal{M}^{<S>} \oplus \mathcal{M}^{<R>})$$
is a little bit delicate. We pick an element m in the kernel, hence we can write it as
$$m = m_1 - Sm_1 = m_2 - R^{-1}m_2$$
and send $m \mapsto m_1 - m_2$ (Here we have to use the orientation). If we modify m_1, m_2 to $m_1' = m_1 + n_1, m_2' = m_2 + n_2$ then $m_1' - m_2'$ gives the same element in $\mathcal{M}/(\mathcal{M}^{<S>} \oplus \mathcal{M}^{<R>})$.

This answer can only be right if $m_1 - m_2$ goes to zero under the map r, i.e. we have to show that
$$m_1 - m_2 - S(m_1 - m_2) \in (\mathrm{Id}-T)\mathcal{M}$$

We compute

$$m_1 - m_2 - S(m_1 - m_2) = m - m_2 + Sm_2 = m - m_2 + R^{-1}m_2 - R^{-1}m_2 + Sm_2 =$$

$$-R^{-1}m_2 + Sm_2 = -T^{-1}Sm_2 + Sm_2 \in (\mathrm{Id} - T)\mathcal{M}$$

Finally we claim that the map $\mathcal{M}^{<T>} \to \ker(\mathcal{M} \to (\mathcal{M}/(\mathrm{Id}-S)\mathcal{M} \oplus \mathcal{M}/(\mathrm{Id}-R)\mathcal{M}))$ is given by $m \mapsto m - Sm = m - R^{-1}T^{-1}m = m - R^{-1}m$.

There is still another piece of structure. The map $c : z \mapsto \frac{1}{\bar{z}}$ induces an (differentiable) isomorphism of $\mathbb{H}$ and since the isomorphism commutes with the action of Γ in induces an involution on $\Gamma\backslash\mathbb{H}$. The map c can be written as

$$z \mapsto \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \bar{z} = S_1\bar{z} = \overline{S_1 z}$$

We get an isomorphism of cohomology groups

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) \xrightarrow{\sim} H^1(\Gamma\backslash\mathbb{H}, c_*(\tilde{\mathcal{M}})) \tag{2.30}$$

The direct image sheaf $c_*(\tilde{\mathcal{M}})$ is by definition the sheaf attached to the Γ module $\mathcal{M}^{(S_1)}$: This module is equal to $\mathcal{M}$ as an abstract module, but the action is twisted by a conjugation by the above matrix S_1, i.e.

$$\gamma * m = S_1\gamma S_1^{-1}m = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \gamma \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \tag{2.31}$$

But now the map $m \to S_1 m$ provides an isomorphism $\mathcal{M}^{(S_1)} \xrightarrow{\sim} \mathcal{M}$ and hence we get in involution on the cohomology groups

$$c^\bullet : H^\bullet(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) \to H^\bullet(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) \tag{2.32}$$

In our special situation this action is easy to compute. We observe that the matrix S_1 fixes the two points i, ρ and hence the two open sets U_i, U_ρ of the covering. Hence it also fixes $\mathcal{M}^{\Gamma_i}$ and $\mathcal{M}^{\Gamma_\rho}$ and therefore induces an involution on $\mathcal{M}/\mathcal{M}^{\Gamma_i} \oplus \mathcal{M}^{\Gamma_\rho}$, this is our $H^(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})$ and the involution is the complex conjugation.

Final remark: The reader may get the impression that it is easy to compute the cohomology, but the contrary is true. In the case $\Gamma = \mathrm{Sl}_2(\mathbb{Z})/\pm\mathrm{Id}$ we found formulae for the rank of the cohomology groups, this seems to be a satisfactory answer, but it is not. The point is that in the next section we will introduce the Hecke operators, these Hecke operators form an algebra of endomorphisms of the cohomology groups. It is a fundamental question (see further down) to understand the cohomology as a module under the action of this Hecke algebra. It is difficult to write down the effect of a Hecke operator on a module like $\mathcal{M}/(\mathcal{M}^{\Gamma_i} + \mathcal{M}^{\Gamma_\rho})$. We will discuss an explicit example in (3.3.2.)

The situation is even worse if we consider the case $\Gamma = \mathrm{Gl}_2(\mathbb{Z}[i])/\{(i^\nu \mathrm{Id})\}$. First of all we notice that it is not possible to read off the dimensions of the individual groups $H^i(\Gamma\backslash\mathbb{H}_3, \tilde{M})$ from the complex in 2.1.2) . Of course we can compute them in any given case, but our method does not give any kind of theoretical insight.

We will see later that we can prove vanishing theorems $H^i(\tilde{\Gamma}\backslash\mathbb{H}_3, \tilde{M}_\mathbb{C})$ for certain coefficient systems $\tilde{M}_\mathbb{C}$ by transcendental means. These results can not be obtained by our elementary methods.

Chapter 3

Hecke Operators

3.1 The construction of Hecke operators

We mentioned already that the cohomology and homology groups of an arithmetic group has an additional structure. We have the action of the so-called Hecke algebra. The following description of the Hecke algebra is somewhat provisorial, we get a richer Hecke algebra, if we work in the adelic context (See Chap III). But the desription here is more intuitive.

We start from the arithmetic group $\Gamma \subset G(\mathbb{Q})$ and an arbitrary Γ-module $\mathcal{M}$. The module $\mathcal{M}$ is also a module over a ring R which in the beginning may be simply $\mathbb{Z}$.

At this point it is better to have a notation for this action

$$\Gamma \times \mathcal{M} \to \mathcal{M}, (\gamma, m) \mapsto r(\gamma)(m)$$

where now $r : \Gamma \to \mathrm{Aut}(\mathcal{M})$.

We assume that $\mathcal{M}$ is a module over a ring R in which we can invert the orders of the stabilizers of fixed points of elements $\gamma \in \Gamma$.

If we have a subgroup $\Gamma' \subset \Gamma$ of finite index, then we constructed maps

$$\begin{aligned} \pi^{\bullet}_{\Gamma',\Gamma} :& H^{\bullet}(\Gamma\backslash X, \tilde{\mathcal{M}}) \longrightarrow H^{\bullet}(\Gamma'\backslash X, \tilde{\mathcal{M}}) \\ \pi_{\Gamma',\Gamma,\bullet} :& H^{\bullet}(\Gamma\backslash X, \tilde{\mathcal{M}}) \longrightarrow H^{\bullet}(\Gamma'\backslash X, \tilde{\mathcal{M}}) \end{aligned}$$

(see 2.1.1).

We pick an element $\alpha \in G(\mathbb{Q})$. The group

$$\Gamma(\alpha^{-1}) = \alpha^{-1}\Gamma\alpha \cap \Gamma$$

is a subgroup of finite index in Γ and the conjugation by α induces an isomorphism

$$\mathrm{inn}(\alpha) : \Gamma(\alpha^{-1}) \longrightarrow \Gamma(\alpha).$$

We get an isomorphism

$$j(\alpha) : \Gamma(\alpha^{-1})\backslash X \longrightarrow \Gamma(\alpha)\backslash X$$

which is induced by the map $x \longrightarrow \alpha x$ on the space X. This yields an isomorphism of cohomology groups

$$j(\alpha)^{\bullet} : H^{\bullet}(\Gamma(\alpha^{-1})\backslash X, \tilde{\mathcal{M}}) \longrightarrow H^{\bullet}(\Gamma(\alpha)\backslash X, j(\alpha)_*(\tilde{\mathcal{M}})).$$

We compute the sheaf $j(\alpha)_*(\tilde{\mathcal{M}})$. For a point $x \in \Gamma(\alpha)\backslash X$ we have $j(\alpha)_*(\tilde{\mathcal{M}})_x = \tilde{\mathcal{M}}_{x'}$ where $j(\alpha)(x') = X$. We have the projection $\pi_{\Gamma(\alpha^{-1})} : X \to \Gamma(\alpha^{-1})\backslash X$, and the definition yields

$$(\tilde{\mathcal{M}})'_x = \left\{ s : \pi^{-1}_{\Gamma(\alpha^{-1})}(x') \to \mathcal{M} \mid s(\gamma m) = \gamma s(m) \text{ for all } \gamma \in \Gamma(\alpha^{-1} \right\}$$

The map $z \longrightarrow \alpha z$ provides an identification $\pi^{-1}_{\Gamma(\alpha^{-1})}(x') \xrightarrow{\sim} \pi^{-1}_{\Gamma(\alpha)}(x)$ in in terms of this fibre we can describe the stalk at x as

$$j(\alpha)_*(\tilde{\mathcal{M}})_x = \left\{ s : \pi^{-1}_{\Gamma(\alpha)}(x) \to \mathcal{M} \mid s(\gamma v) = \alpha^{-1}\gamma\alpha s(v) \text{ for all } \gamma \in \Gamma(\alpha) \right\}.$$

Hence we see: We may use α to define a new $\Gamma(\alpha)$-module $\mathcal{M}^{(\alpha)}$: The underlying abelian group of $\mathcal{M}^{(\alpha)}$ is $\mathcal{M}$ but the operation of $\Gamma(\alpha)$ is given by

$$(\gamma, m) \longrightarrow (\alpha^{-1}\gamma\alpha)m = \gamma *_\alpha m.$$

Then we have obviously that the sheaf $j(\alpha)_*(\tilde{\mathcal{M}})$ is equal to $\tilde{\mathcal{M}}^{(\alpha)}$. Hence we see that every element

$$u_\alpha \in \operatorname{Hom}_{\Gamma(\alpha)}(\mathcal{M}^{(\alpha)}, \mathcal{M})$$

defines a map $\tilde{u}_\alpha : j(\alpha)_*(\tilde{\mathcal{M}}) \to \tilde{\mathcal{M}}$. Hence we get a diagram

$$\begin{array}{ccccc}
H^\bullet(\Gamma(\alpha^{-1})\backslash X, \tilde{\mathcal{M}}) & \xrightarrow{j(\alpha)^\bullet} & H^\bullet(\Gamma(\alpha)\backslash X, j(\alpha)_*(\tilde{\mathcal{M}})) & \xrightarrow{\tilde{u}^\bullet_\alpha} & H^\bullet(\Gamma(\alpha)\backslash X, \mathcal{M}) \\
\uparrow \pi^\bullet & & & & \downarrow \pi_\bullet \\
H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}}) & & \xrightarrow{\quad T(\alpha, u_\alpha) \quad} & & H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})
\end{array}$$

where the operator on the bottom line is the Hecke operator. It depends on two data, namely, the element $\alpha \in G(\mathbb{Q})$ and the choice of $u_\alpha \in \operatorname{Hom}_{\Gamma(\alpha)}(\mathcal{M}^{(\alpha)}, \mathcal{M})$.

It is not difficult to show that the operator $T(\alpha, u_\alpha)$ depends only on the double coset $\Gamma\ \alpha\ \Gamma$, provided we adapt the choice of u_α. To be more precise if

$$\alpha_1 = \gamma_1 \alpha \gamma_2 \qquad\qquad \gamma_1, \gamma_2 \in \Gamma,$$

then we have an obious bijection

$$\Phi_{\gamma_1,\gamma_2} : \operatorname{Hom}_{\Gamma(\alpha)}(\mathcal{M}^{(\alpha)}, \mathcal{M}) \longrightarrow \operatorname{Hom}_{\Gamma(\alpha_1)}(\mathcal{M}^{\alpha_1)}, \mathcal{M})$$

which is given by

$$\Phi_{\gamma_1,\gamma_2}(u_\alpha) = u_{\alpha_1} = \gamma_1 u_\alpha \gamma_2.$$

The reader will verify without difficulties that

$$T(\alpha, u_\alpha) = T(\alpha_1, u_{\alpha_1}).$$

(Verify this for H^0 and then use some kind of resolution)

There is a case where we have also a rather obvious choice of u_α. This is the case if $R \subset \mathbb{Q}$ and our Γ-module $\mathcal{M}$ is a R-lattice in the $\mathbb{Q}$-vector space $\mathcal{M}_\mathbb{Q}$, where $\mathcal{M}_{\mathbb{Q}}$ is a rational $G(\mathbb{Q})$ module, i.e. is obtained from a rational (finite dimensional) representation of our group $G/\mathbb{Q}$.

Then we have the canonical choice of an

$$u_{\alpha,\mathbb{Q}} : \mathcal{M}_{\mathbb{Q}}^{(\alpha)} \longrightarrow \mathcal{M}_{\mathbb{Q}},$$

which is given by $m \mapsto \alpha m$. But this morphism will not necessarily map the lattice $\mathcal{M}^{(\alpha)}$ into $\mathcal{M}$. It is also bad if $u_{\alpha,\mathbb{Q}}$ maps $\mathcal{M}^{(\alpha)}$ into $b\mathcal{M}$, where b is an integer > 1. But then we can find a unique rational number $d(\alpha) > 0$ for which

$$d(\alpha) \cdot u_{\alpha,\mathbb{Q}} : \mathcal{M}^{(\alpha)} \longrightarrow \mathcal{M} \text{ and } d(\alpha) \cdot u_{\alpha,\mathbb{Q}}(\mathcal{M}^{(\alpha)}) \not\subset b\mathcal{M} \text{ for any integer } b > 1.$$

Then $u_\alpha = d(\alpha) \cdot u_{\alpha,\mathbb{Q}}$ is called the *normalized* choice. The canonical choice defines endomorphisms on the rational cohomology, i.e. the cohomology with coefficients in $\tilde{\mathcal{M}}_{\mathbb{Q}}$ whereas the normalized Hecke operators induce endomorphism of the integral cohomology.

We see that we can construct many endomorphisms $T(\alpha, u_\alpha) : H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}}) \to H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})$. These endomorphisms will generate an algebra

$$\mathcal{H}_{\Gamma,\tilde{\mathcal{M}}} \subset \operatorname{End}(H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})).$$

This is the so-called Hecke algebra. We can also define endomorphisms $T(\alpha, u_\alpha)$ on the cohomology with compact supports, on the inner cohomology and the cohomology of the boundary. Since the operators are compatible with all the arrows in the fundamental exact sequence we denote them by the same symbol.

We now assume that $\mathcal{M}$ is a finitely generated R module where R is the ring of integers in an algebraic number field K/Q. Then our cohomology groups $H^q(\Gamma\backslash X, \tilde{\mathcal{M}})$ are finitely generated R-modules with an action of the algebra $\mathcal{H}$ on it. The Hecke algebra also acts on the inner cohomology $H^q_!(\Gamma\backslash X, \tilde{\mathcal{M}})$ If we tensorize our coefficient system with any number field $L \supset K$, then we write $M_L = M \otimes L$.

We state without proof : $\boxed{\text{He-ss}}$

Theorem 3.1.1. *Let $\mathcal{M}$ be a module obtained by a rational representation. For any extension $L/K/\mathbb{Q}$ the $\mathcal{H}_\Gamma \otimes L$ module $H^q_!(\Gamma\backslash X, \tilde{\mathcal{M}}_L)$ is semi simple, i.e. a direct sum of irreducible $\mathcal{H}_\Gamma$ modules.*

The proof of this theorem will be discussed in Chap.III section 4, it requires some input from analysis. We tensorize our coefficient system by $\mathbb{C}$, i.e. we consider $\mathcal{M}_L \otimes_L \mathbb{C} = \mathcal{M}_{\mathbb{C}}$. Let us assume that Γ is torsion free. First of all start from the well known fact, that the cohomology $H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}}_{\mathbb{C}})$ can be computed from the de-Rham-complex

$$H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}}_{\mathbb{C}}) = H^\bullet(\Omega^\bullet \otimes \tilde{\mathcal{M}}_{\mathbb{C}}(\Gamma\backslash X)).$$

We introduces some specific positive definite hermitian form on $\mathcal{M}_{\mathbb{C}}$ and this allows us to define a hermitian scalar product between two $\tilde{\mathcal{M}}_{\mathbb{C}}$ -valued p-forms

$$< \omega_1, \omega_2 >= \int_{\Gamma\backslash X} \omega_1 \wedge *\omega_2,$$

provided one of the forms is compactly supported.

This will give us a positive definite scalar product on $H^p_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n,\mathbb{C}})$, In the classical case of Gl_2 this is the Peterson scalar product. Finally we show that $\mathcal{H}_\Gamma$ is self adjoint with respect to this scalar product, and then semi-simplicity follows from the standard argument.

3.1.1 Commuting relations

We want to say some words concerning the structure of the Hecke algebra.

To begin we discuss the action of the Hecke-algebra on $H^0(\Gamma\backslash X, \tilde{\mathcal{M}})$. We have to do this since we defined the cohomology in terms of injective (or acyclic) resolutions and therefore the general results concerning the structure of the Hecke algebra can be reduced to this special case.

If we have a Γ-module $\mathcal{M}$ and if we look at the diagram defining the Hecke operators, then we see that we get in degree 0

$$\begin{array}{ccc} \mathcal{M}^{\Gamma(\alpha^{-1})} & \longrightarrow (\mathcal{M}^{(\alpha)})^{\Gamma(\alpha)} \xrightarrow{u_\alpha} & \mathcal{M}^{\Gamma(\alpha)} \\ \uparrow & & \downarrow \\ \mathcal{M}^{\Gamma} & \xrightarrow{\qquad T(\alpha,u_\alpha) \qquad} & \mathcal{M}^{\Gamma} \end{array}$$

where the first arrow on the top line is induced by the identity map $\mathcal{M} \to \mathcal{M}^{(\alpha)} = \mathcal{M}$ and the second by a map $u_\alpha \in \mathrm{Hom}_{\mathbf{Ab}}(\mathcal{M}, \mathcal{M})$ which satisfies $u_\alpha((\alpha\gamma\alpha^{-1})m) = \gamma u_\alpha(m)$. Recalling the definition of the vertical arrow on the right, we find

$$T(\alpha, u_\alpha)(v) = \sum_{\gamma\in\Gamma/\Gamma(\alpha)} \gamma \cdot u_\alpha(v).$$

We are interested to get formulae for the product of Hecke oprators, so, for instance, we would like to show that under certian assumptions on α, β and certain adjustment of u_α, u_β and $u_{\alpha\beta}$ we can show

$$T(\alpha, u_\alpha) \cdot T(\beta, u_\beta) = T(\beta, u_\beta) \cdot T(\alpha, u_\alpha) = T(\alpha\beta, u_{\alpha\beta}).$$

It is easy to see what the conditions are if we want such a formula to be true. We look at what happens in H^0 and get

$$T(\alpha, u_\alpha) \cdot T(\beta, u_\beta)(v) = \sum_{\gamma\in\Gamma/\Gamma(\alpha)} \sum_{\eta\in\Gamma/\Gamma(\beta)} \gamma u_\alpha \cdot \eta u_\beta(v).$$

We rewrite the right hand slightly illegally:

$$\sum_{\gamma\in\Gamma/\Gamma(\alpha)} \sum_{\eta\in\Gamma/\Gamma(\beta)} \gamma u_\alpha \eta u_\alpha^{-1} u_\alpha u_\beta(v),$$

where we have to take into account that this does not make sense because the term $\gamma u_\alpha \eta u_\alpha^{-1}$ is not defined. But let us assume that (i) for each η we can find an η' such that

$$\eta' \circ u_\alpha = u_\alpha \circ \eta,$$

where these η' also form a sytem of representatives for $\Gamma/\Gamma(\beta)$ (ii) The elements $\gamma\eta'$ and $\eta'\gamma$ form a system of representatives for $\Gamma/\Gamma(\alpha\beta)$ (iii) $u_\alpha u_\beta(v) = u_\beta u_\alpha(v) = u_{\alpha\beta}(v)$, then we get a legal rewrite

$$T(\alpha, u_\alpha)\cdot T(\beta, u_\beta)(v) = \sum_{\gamma\in\Gamma/\Gamma(\alpha)}\sum_{\eta'\in\Gamma/\Gamma(\beta)}\gamma\eta' u_\alpha u_\beta(v) = \sum_{\xi\in\Gamma/\Gamma(\alpha\beta)}\xi u_{\alpha\beta}(v) = T(\alpha\beta, u_{\alpha\beta})(v)$$

We want to explain in a special case that we may have relations like the one above.

Let S be a finite set of primes, let $|S|$ be the product of these primes. Then we define $\Gamma_S = G(\mathbb{Z}[\frac{1}{|S|}])$. We say that $\alpha \in G(\mathbb{Q})$ has support in S if $\alpha \in G(\mathbb{Z}[\frac{1}{|S|}])$.

We take the group $\Gamma = \mathrm{Sl}_d(\mathbb{Z})$, and we take two disjoint sets of primes S_1, S_2. For the group Γ one can prove the so-called strong approximation theorem which asserts that for any natural number m the map

$$\mathrm{Sl}_d(\mathbb{Z}) \longrightarrow \mathrm{Sl}_d(\mathbb{Z}/m\mathbb{Z})$$

is surjective. (This special case is actually not so difficult. The theorem holds for many other arithmetic groups, for instance for simply connected Chevalley schemes over $\mathrm{Spec}(\mathbb{Z})$.)

We consider the case

$$\alpha = \begin{pmatrix} a_1 & & & \\ & a_2 & & \\ & & \ddots & \\ & & & a_d \end{pmatrix} \in \Gamma_{S_1}, \beta = \begin{pmatrix} b_1 & & & \\ & b_2 & & \\ & & \ddots & \\ & & & b_d \end{pmatrix} \in \Gamma_{S_2},$$

where $a_d|a_{d-1}\dots|a_1$ and $b_d|b_{d-1}|\dots|b_1$. It is clear that we can find integers n_1 and n_2 which are only divisible by the primes in S_1 and S_2 respectively, so that

$$\Gamma(n_i) \subset \Gamma(\alpha^{-1}), \Gamma(n_2) \subset \Gamma(\beta^{-1}),$$

where the $\Gamma(n_i)$ are the full congruence subgroups $\mod n_1$ and n_2 respectively. Since we have

$$\mathrm{Sl}_d(\mathbb{Z}/n\mathbb{Z}) = \mathrm{Sl}_d(\mathbb{Z}/n_1\mathbb{Z}) \times \mathrm{Sl}_d(\mathbb{Z}/n_2\mathbb{Z})$$

we get

$$\Gamma/\Gamma(\alpha^{-1}\beta^{-1}) \xrightarrow{\sim} \Gamma/\Gamma(\alpha^{-1}) \times \Gamma/\Gamma(\beta^{-1}).$$

On the right hand side we can chose representatives γ for $\Gamma/\Gamma(\alpha^{-1})$ which satisfy $\gamma \equiv \mathrm{Id} \mod n_2$ and η for $\Gamma/\Gamma(\beta^{-1})$ which satisfy $\eta \equiv \mathrm{Id} \mod n_1$. Then the products $\gamma\eta$ will form a system of representatives for $\Gamma/\Gamma(\alpha^{-1}\beta^{-1})$. But then we clearly have $u_\alpha\eta = \eta u_\alpha$ and we see that (i) and (ii) above are true. Then we can put $u_{\alpha\beta} = u_\alpha u_\beta$.

We consider the case that our module $\mathcal{M}$ is a R-lattice in $\mathcal{M}_{\mathbb{Q}}$, where $\mathcal{M}_{\mathbb{Q}}$ is a rational $G(\mathbb{Q})$-module. Then we saw that we can write

$$u_\alpha = d(\alpha)\cdot\alpha$$

where $d(\alpha)$ will be a product of powers of the primes p dividing n_1 and an anologous statement can be obtained for β and n_2.

Since we have $\alpha\beta = \beta\alpha$ and since clearly $d(\alpha)d(\beta) = d(\alpha\beta)$ we also get the commutation relation.

Of course we have to be careful here. We only proved it for the rather uninteresting case of $H^0(\Gamma\backslash X, \mathcal{M})$. If we want to prove it for cohomology in higher degrees, we have to choose an acyclic resolution

$$0 \longrightarrow \mathcal{M} \longrightarrow A^0 \longrightarrow A^1 \longrightarrow \ldots,$$

We have to extend the maps u_α, u_β to this complex

$$\begin{array}{ccccc} 0 \longrightarrow & \mathcal{M}^{(\alpha)} & \longrightarrow & (A^\bullet)^{(\alpha)} \\ & \Big\downarrow u_\alpha & & \Big\downarrow u_\alpha \\ 0 \longrightarrow & \mathcal{M} & \longrightarrow & A^\bullet, \end{array}$$

and we have to prove that the relation

$$u_\alpha \eta u_\beta = \eta' u_\alpha u_\beta = \eta' u_{\alpha\beta}$$

also holds on the complex. If we can prove this, it becomes clear that the commutation rule also holds in higher degrees.

We choose the special resolution

$$0 \longrightarrow \mathcal{M} \longrightarrow \ \mathrm{Ind}_1^\Gamma \mathcal{M} \longrightarrow .$$

It is clear that if suffices to show: If we selected the u_α, u_β in such a way that we have the condition (i), (ii) and (iii) above satisfied, then we can choose extensions $u_\alpha, u_\beta, u_{\alpha\beta}$ to $\mathrm{Ind}_1^\Gamma \mathcal{M}$ so that (i), (ii) and (iii) are also satisfied. Once we have done this we can proceed by induction.

We have the diagram of $\Gamma(\alpha)$-modules

$$\begin{array}{ccccc} 0 \longrightarrow & \mathcal{M}^{(\alpha)} & \longrightarrow & (\ \mathrm{Ind}_1^\Gamma \mathcal{M})^{(\alpha)} \\ & \Big\downarrow u_\alpha & & \Big\downarrow ? \\ 0 \longrightarrow & \mathcal{M} & \longrightarrow & \mathrm{Ind}_1^\Gamma \mathcal{M}, \end{array}$$

and we are searching for a suitable vertical arrow ?. The horizontal arrows are given by (as before)

$$i : m \longrightarrow f_m : \{\gamma \longrightarrow \gamma m\}.$$

To get a map

$$? \in \ \mathrm{Hom}_{\Gamma(\alpha)}\left(\left(\ \mathrm{Ind}_1^\Gamma m\right)^{(\alpha)},\ \mathrm{Ind}_1^\Gamma \mathcal{M}\right)$$

we apply Frobenius reciprocity: We choose representatives $\gamma_1 \ldots \gamma_m$ of $\Gamma/\Gamma(\alpha)$; then our $\Gamma(\alpha)$-module in the second argument is

$$\mathrm{Ind}_1^\Gamma \mathcal{M} \simeq \bigoplus_{\gamma_i} \ \mathrm{Ind}_1^{\Gamma(\alpha)} \mathcal{M}$$

where $f \in \operatorname{Ind}_1^\Gamma \mathcal{M}$ is mapped to $(f_1, \ldots, f_m) \in \operatorname{Ind}_1^{\Gamma(\alpha)}$, and where

$$f_i(\gamma) = f(\gamma_i \gamma).$$

Hence we have

$$\operatorname{Hom}_{\Gamma(\alpha)}\left(\left(\operatorname{Ind}_1^\Gamma \mathcal{M}\right)^{(\alpha)}, \operatorname{Ind}_1^\Gamma \mathcal{M}\right) \simeq \bigoplus_{x_i} \operatorname{Hom}_{\{1\}}\left(\operatorname{Ind}_1^\Gamma \mathcal{M}, \mathcal{M}\right).$$

an element $\Phi_{\gamma_i} : \operatorname{Hom}_{\{1\}}(\operatorname{Ind}_1^\Gamma \mathcal{M}, \mathcal{M})$ is a collection of homomorphisms

$$\varphi_{\gamma_i,\gamma} : \mathcal{M} \longrightarrow \mathcal{M},$$

so that almost all of them are zero on $\Phi_{\gamma_i}(f) = \varphi_{\gamma_i,\gamma}(f(\gamma)$. The homomorphism

$$i \circ u_\alpha \in \operatorname{Hom}_{\Gamma(\alpha)}(\mathcal{M}^{(\alpha)}, \operatorname{Ind}_1^\Gamma \mathcal{M}) = \operatorname{Hom}_{\{1\}}(\mathcal{M}, \oplus_{\gamma_1} \mathcal{M})$$

is by definition given by the vector of maps

$$m \longrightarrow (\ldots, f_{u_\alpha(m)}(\gamma_i), \ldots) = (\ldots \gamma_i u_\alpha(m), \ldots).$$

Hence we define ??? by the conditions that

$$\varphi_{\gamma_i,\gamma} : m \longrightarrow \begin{cases} \gamma_i u_\alpha(m) & \text{for } \gamma = 1 \\ \\ 0 & \text{for } \gamma \neq 1, \end{cases}$$

and we get the required commutative diagram. This morphism ? is now the extension of $u_\alpha : \mathcal{M}^{(\alpha)} \to \mathcal{M}$ to $(\operatorname{Ind}_{\{1\}}^\Gamma \mathcal{M})^{(\alpha)} \longrightarrow \operatorname{Ind}_{\{1\}}^\Gamma \mathcal{M}$. It is clear that under the assumption (i), (ii), (iii) for the morphisms $u_\alpha : \mathcal{M}^{(\alpha)} \to \mathcal{M}$ and $u_\beta : \mathcal{M}^{(\beta)} \to \mathcal{M}$ the extensions also satisfy (i), (ii), (iii).

Hence we see that under our special assumptions on α, β we have

$$T(\beta, u_\beta) \cdot T(\alpha, u_\alpha) = T(\beta\alpha, u_{\beta\alpha})$$

on all the cohomology groups $H^\bullet(\mathrm{Sl}_d(\mathbb{Z}) \backslash X, \tilde{\mathcal{M}})$.

3.1.2 Relations between Hecke operators

We attach a Hecke operator to any coset $\Gamma\alpha\Gamma$ where $\alpha \in \mathrm{Gl}_2^+(\mathbb{Q})$ (i.e. $\det(\alpha) > 0$, we want α to act on the upper half plane). The center of $\mathrm{Gl}_2(\mathbb{Q})$ is $\mathbb{Q}^\times$. It acts trivially on $\mathcal{M}_n$ this will have te effect that α and $\lambda\alpha$ with $\lambda \in \mathbb{Q}^*$ define the same operator. (Of course here we assume that $m = -n/2$.) Hence we may assume that the matrix entries of α are integers. The theorem of elementary divisors asserts that the double cosets

$$\Gamma \cdot M_n(\mathbb{Z})_{\det \neq 0} \cdot \Gamma \subset \mathrm{Gl}_2^+(\mathbb{Q})$$

are represented by matrices of the form

$$\begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}$$

where $b \mid a$. But here we can divide by b, and we are left with the matrix

$$\alpha = \begin{pmatrix} a & 0 \\ 0 & 1 \end{pmatrix} \quad , \quad a \in \mathbb{N}.$$

We can attach a Hecke operator to this matrix provided we choose u_α. We see that α induces on the basis vectors

$$X^\nu Y^{n-\nu} \longrightarrow a^{\nu - n/2} \cdot X^\nu Y^{n-\nu}.$$

Hence we see that we have the following natural choice for u_α

$$u_\alpha : P(X.Y) \longrightarrow a^{n/2}\alpha \cdot P(X,Y).$$

(See the general discussion of the Hecke operators)

Hence we get a family of endomorphisms

$$T\left(\begin{pmatrix} a & 0 \\ 0 & 1 \end{pmatrix}, u_{\begin{pmatrix} a & 0 \\ 0 & 1 \end{pmatrix}}\right) = T(a)$$

of the cohomology $H^i(\Gamma\backslash\mathbb{H}, \mathcal{M}_n)$.

We have seen already that we have $T_a T_b = T_{ab}$ if a, b are coprime.

Hence we have to investigate the local algebra $\mathcal{H}_p$ which is generated by the

$$T_{p^r} = T\left(\begin{pmatrix} p^r & 0 \\ 0 & 1 \end{pmatrix}, u_{\begin{pmatrix} p^r & 0 \\ 0 & 1 \end{pmatrix}}\right)$$

for the special case of the group $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$ and the coefficient system $\mathcal{M}_n$. To do this we compute the product

$$T_{p^r} \cdot T_p = T\left(\begin{pmatrix} p^r & 0 \\ 0 & 1 \end{pmatrix}, u_{\alpha_p^r}\right) \cdot T\left(\begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix}, u_{\alpha_p}\right)$$

where the $u'_\alpha r$ are the canonical choices.

Again we investigate first what happens in degree zero, i.e. on $H^0(\Gamma\backslash\mathbb{H}, \tilde{I})$ where I is any Γ-module.

Let $\alpha = \begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix}$, then we have

$$T(\alpha^r, u_{\alpha^r})T(\alpha, u_\alpha)\xi = (\sum_{\gamma \in \Gamma/\Gamma(\alpha^r)} \gamma u_{\alpha^r})(\sum_{\eta \in \Gamma/\Gamma(\alpha)} \eta u_\alpha)(\xi)$$

We have the classical system of representatives

$$\Gamma/\Gamma(\alpha^r) = \bigcup_{j \mod p^r} \begin{pmatrix} 1 & j \\ 0 & 1 \end{pmatrix} \Gamma(\alpha^r) \;\cup\; \bigcup_{j' \mod p^{r-1}} \begin{pmatrix} 1 & 0 \\ j'p & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \Gamma(\alpha^r)$$

Then our product of Hecke operators becomes

$$(\sum_{j \mod p^r} \begin{pmatrix} 1 & j \\ 0 & 1 \end{pmatrix} + \sum_{j' \mod p^{r-1}} \begin{pmatrix} 1 & 0 \\ j'p & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} u_{\alpha^r})(\sum_{j_1 \mod p} \begin{pmatrix} 1 & j_1 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix})u_\alpha(\xi) =$$

$$(\sum_{j \mod p^r, j_1 \mod p} \begin{pmatrix} 1 & j \\ 0 & 1 \end{pmatrix} u_{\alpha^r} \begin{pmatrix} 1 & j_1 \\ 0 & 1 \end{pmatrix} u_\alpha)(\xi)$$

$$+(\sum_{j \mod p^r} \begin{pmatrix} 1 & j \\ 0 & 1 \end{pmatrix} u_{\alpha^r} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix})u_\alpha(\xi)+$$

$$(\sum_{j' \mod p^{r-1}, j_1 \mod p} \begin{pmatrix} 1 & 0 \\ j'p & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} u_{\alpha^r} \begin{pmatrix} 1 & j_1 \\ 0 & 1 \end{pmatrix} u_\alpha)(\xi)+$$

$$(\sum_{j' \mod p^{r-1}} \begin{pmatrix} 1 & 0 \\ j'p & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} u_{\alpha^r} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} u_\alpha)(\xi)$$

Now we have to assume the validity of certain commutation rules

$$\begin{aligned} u_{\alpha^r} \begin{pmatrix} 1 & j_1 \\ 0 & 1 \end{pmatrix} &= \begin{pmatrix} 1 & j_1 p^r \\ 0 & 1 \end{pmatrix} u_{\alpha^r} \\ u_{\alpha^r} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} u_\alpha \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} &= p^n u_{\alpha^{r-1}} \end{aligned} \qquad (*)$$

which are obviously valid for the canonical choices in the case $I = \mathcal{M}_k[m]$ (here m is arbitrary). We also have $u_{\alpha^r} u_\alpha = u_{\alpha^{r+1}}$. If we exploit the first commutation relation then we get as the sum of the first summand and the third summand

$$\sum_{j \mod p^r, j_1 \mod p} \begin{pmatrix} 1 & j + p^r j_1 \\ 0 & 1 \end{pmatrix} u_{\alpha^{r+1}} +$$

$$\sum_{j' \mod p^{r-1}, j_1 \mod p} \begin{pmatrix} 1 & 0 \\ (j' + p^{r-1} j_1)p & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} u_{\alpha^{r+1}},$$

and this is $T_{p^{r+1}}$. To compute the contribution of the second and the fourth summand we observe that $w = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \in \Gamma$ and hence we have $w\xi = \xi$. Now the second commutation relation yields for the sum of the second term and the fourth term

$$p^n(\sum_{j \mod p^r} \begin{pmatrix} 1 & j \\ 0 & 1 \end{pmatrix} u_{\alpha^{r-1}} + \sum_{j' \mod p^{r-1}} \begin{pmatrix} 1 & 0 \\ j'p & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} u_{\alpha^{r-1}})$$

If we take into account that our summation over the j(resp. j') is $\mod p^r$(resp. $\mod p^{r-1}$), then we see that this second expression yields $p^{n+1}T_{p^{r-1}}$, provided $r > 1$. If $r = 1$ then the summation over p^{r-1} is the same as the summation over p^{r-2} and then the second term is $(1 + 1/p)T_{p^0}$

If we put $e(r) = 0$ for $r > 1$ and $e(1) = 1$ then we arrive at the formula

$$T_{p^r} \cdot T_p = T_{p^{r+1}} + (1 + \frac{e(r)}{p})p^{n+1}T_{p^{r-1}}$$

This formula is valid for all values of $r \geq 0$ if we put $T_{p^{-1}} = 0$.

We proved the formulae for the $H^0(\Gamma\backslash\mathbb{H}, \tilde{I})$ for any Γ module I for which we can choose the u_α satisfy the commutation rules (*). These commutation rules are satisfied for the canonical choice in the case of $I = \mathcal{M}_n[m]$. But then it is not so difficult to see that we can embed $\mathcal{M}_n$ into an acyclic Γ-module I_0 such that we can extend the $u_\alpha : \mathcal{M}_n^{(\alpha)} \to \mathcal{M}_n$ to $I_0^{(\alpha)} \to I_0$ such that the commutation rules are still valid. Then we get induced morphisms $u_\alpha : (I_0/\mathcal{M}_n)^{(\alpha)} \to (I_0/\mathcal{M}_n)$ and also on these quotient the commutation rules hold. Then we see from the resulting exact sequence that our formulae for the Hecke operators are also true for the action on $H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}_n})$.

It may be illustrative to generalize a little bit. We choose an integer $N > 1$ and we take as our arithmetic group the congruence group $\Gamma = \Gamma(N)$. For any prime $p \not| N$ the $T(\alpha, u_\alpha)$ with $\alpha \in \mathrm{Gl}_2^+(\mathbb{Z}[1/p])$ form a commutative subalgebra $\mathcal{H}_p$ which is generated by T_p. For $p|N$ we can also consider the $T(\alpha, u_\alpha)$ with $\alpha \in \mathrm{Gl}_2^+(\mathbb{Z}[1/p])$. They will also generate a local algebra $\mathcal{H}_p$ of endomorphisms in any of our cohomology groups, but this algebra will not necessarily be commutative. But we saw that the $\mathcal{H}_p, \mathcal{H}_{p_1}$ commute with eachother for two different primes p, p_1. All these algebras $\mathcal{H}_p$ have an identity element e_p, we form the algebra

$$\mathcal{H}_\Gamma = \bigotimes_p{}' \mathcal{H}_p$$

where the superscript indicates that a tensor has an e_p for almost all p. This algebra acts on all our cohomology groups. The algebra $\mathcal{H}$ of endomorphism of one of our cohomology group is a homomorphic image of $\mathcal{H}_\Gamma$.

We come back to this after a brief recapitulation of the theory of semi simple modules.

3.2 Some results on semi-simple modules for algebras

We need a few results from the theory of algebras $\mathfrak{A}$ acting on finite dimensional vector spaces over a field L. Let $\bar{L}$ be an algebaic closure of L.

Let be a finite dimensional vector space V over some field L and an L-algebra $\mathfrak{A}$ with identity acting on V by endomorphisms. We say that the action of $\mathfrak{A}$ on V is semisimple, if the action of $\mathfrak{A} \otimes \bar{L}$ on $V \otimes \bar{L}$ is semi simple and this means that any $\mathfrak{A}$ submodule $W \subset V \otimes \bar{L}$ has a complement. Then it is clear that we get a decomposition indexed by a finite set E

$$V \otimes \bar{L} = \bigoplus_{i \in E} W_i$$

where the W_i are irreducible submodules, i.e. they do not contain any non trivial $\mathfrak{A}$ submodule.

This decomposition will not be unique in general. For any two W_i, W_j of these submodules we have (Schur lemma)

$$\mathrm{Hom}_{\mathfrak{A}}(W_i, W_j) = \begin{cases} \bar{L} & \text{if they are isomorphic as } \mathfrak{A} \text{ -modules} \\ 0 & \text{else} \end{cases}$$

We decompose the indexing set $E = E_1 \cup E_2 \cup .. \cup E_k$ according to isomorphism types. For any E_ν we choose an $\mathfrak{A}$ module $W_{[\nu]}$ of this given isomorphism type. Then by definition

$$\mathrm{Hom}_{\mathfrak{A}}(W_{[\nu]}, W_j) = \begin{cases} \bar{L} & \text{if } j \in E_\nu \\ 0 & \text{else} \end{cases} .$$

Now we define $H_{[\nu]} = \mathrm{Hom}_{\mathfrak{A}}(W_{[\nu]}, V \otimes \bar{L})$ we get an inclusion $H_{[\nu]} \otimes W_{[\nu]}$ whose image X_ν will be an $\mathfrak{A}$ submodule, which is a direct sum of copies of $W_{[\nu]}$.

We get a direct sum decomposition

$$V \otimes \bar{L} = \bigoplus_\nu \bigoplus_{i \in E_\nu} W_i = \bigoplus_\nu X_\nu$$

then this last decomposition is easily seen to be unique, it is called the isotypical decomposition.

If V is a semi simple $\mathfrak{A}$ module then any submodule $W \subset V$ also has a complement (this is not entirely obvious because by definition only $W_{\bar{L}}$ has a complement in $V_{\bar{L}}$. But a small moment of meditation gives us that finding such a complement is the same as solving an inhomogenous system of linear equations over L. If this system has a solution over $\bar{L}$ it also has a solution over L.) and hence we also can decompose the $\mathfrak{A}$ module V into irreducibles. Again we can group the irreducibles according to isomorphism types and we get an isotypical decomposition

$$V = \bigoplus_{i \in E} U_i = \bigoplus_\nu \bigoplus_{i \in E_\nu} U_i = \bigoplus_\nu Y_\nu.$$

But an irreducible $\mathfrak{A}$ module W may become reducible if we extend the scalars to $\bar{L}$. So it may happen that som of our U_i decompose further. Since it is clear that for any two $\mathfrak{A}$- modules V_1, V_2 we have

$$\mathrm{Hom}_{\mathfrak{A}}(V_1, V_2) \otimes \bar{L} = \mathrm{Hom}_{\mathfrak{A} \otimes \bar{L}}(V_1 \otimes \bar{L}, V_2 \otimes \bar{L})$$

we know that we get the isotypical decomposition of $V \otimes \bar{L}$ by taking the isotypical decomposition of the $Y_\nu \otimes \bar{L}$ and then taking the direct sum over ν.

Example: Let L_1/L be a finite extension of degree > 1, then we put $\mathfrak{A} = L_1$ and $V = L_1$, the action is given by multiplication. Clearly V is irreducible, but $V \otimes \bar{L}$ is not. If L_1/L is separable then the module is semisimple, otherwise it is not.

We say that the $\mathfrak{A}$ - module V is absolutely irreducible, if the $\mathfrak{A} \otimes \bar{L}$- module $V \otimes \bar{L}$ is irreducible. In this case it we have a classical result:

Proposition. *Let V be a semi simple $\mathfrak{A}$ module. Then the following assertions are equivalent*
i) The $\mathfrak{A}$ module V is absolutely irreducible
ii) The image of $\mathfrak{A}$ in the ring of endomorphisms is $End(V)$
iii) The vector space of $\mathfrak{A}$ endomorphisms $End_{\mathfrak{A}}(V) = L$.

This can be an exercise for an algebra class. Where do we need the assumption that V is semi simple?

Proposition: *For any semi -simple $\mathfrak{A}$ module V we can find a finite extension L_1/L such that the irreducible sub modules in the decomposition into irreducibles are absolutely irreducible.*

Let us now assume that we have two algebras $\mathfrak{A}, \mathfrak{B}$ acting on V, let us assume that these two operations commute i.e. for $A \in \mathfrak{A}, B \in \mathfrak{B}, v \in V$ we have $A(Bv) = B(Av)$. This structure is the same as having a $\mathfrak{A} \otimes_L \mathfrak{B}$ structure on V. Let us assume that $\mathfrak{A}$ acts semi simply on V and let us assume that the irreducible $\mathfrak{A}$ submodules of V are absolutely irreducible. Then it is clear that the isotypical summands $Y_\nu = \bigoplus W_i$ are invariant under the action $\mathfrak{B}$. Now we pick an index i_0 then the evaluation maps gives us a homomorpism

$$W_{i_0} \otimes \operatorname{Hom}_{\mathfrak{A}}(W_{i_0}, Y_\nu) \to Y_\nu.$$

Under our assumptions this is an isomorphism. Then we see that we get

$$V = \bigoplus_\nu W_{i_\nu} \otimes \operatorname{Hom}_{\mathfrak{A}}(W_{i_0}, Y_\nu)$$

where i_ν is any element in E_ν and where $\mathfrak{A}$ acts upon the first factor and $\mathfrak{B}$ acts upon the second factor via the action of $\mathfrak{B}$ on Y_ν.

Especially we see:

Proposition *If V is an absolutely irreducible $\mathfrak{A} \otimes_L \mathfrak{B}$ module then $V \xrightarrow{\sim} X \otimes Y$, where X (resp, Y) is an absolutely $\mathfrak{A}$ (resp. $\mathfrak{B}$) module*

We apply these considerations to get
$\boxed{\text{Heckess}}$

Theorem 3.2.1. *For any L we can decompose :*

$$H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n,L}) = \bigoplus H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n,L})(\Pi_f)$$

where this is the isotypical decomposition and the Π_f are isomorphism classes of irreducible modules. There is a finite extension $L/\mathbb{Q}$ such that all the isomorphism classes of isotypical modules which occur are actually absolutely irreducible.

If Π_f is an absolutely irreducible $\mathcal{H}_\Gamma$ module then it is the tensor product $\Pi_f = \otimes \pi_p$ where the π_p are absolutely irreducible $\mathcal{H}_p$ modules. For $p \not| N$ the modules π_p are of dimension one (see above theorem) and they are determined by a number $\lambda(\pi_p) \in \mathcal{O}_L$ which is the eigenvalue of T_p on π_p.

This follows easily from our previous considerations. The eigenvalues $\lambda(\pi_p)$ are algebraic integers because T_p induces an endomorphism of $H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n,\mathcal{O}_L})$

which after tensorization with L becomes the T_p on the rational vector space. The above field extension is called the splitting field of $\mathcal{H}_\Gamma$.

These two theorems 2 and 3 are special cases of more general results. We can start from an arbitrary reductive groups over $\mathbb{Q}$, arbitrary congruence subgroups $\Gamma \subset G(\mathbb{Q})$ and arbitrary coefficient systems $\mathcal{M}$ obtained from a rational representation of $G/\mathbb{Q}$, they are finitely generated modules over $\mathbb{Z}$. Then we can consider certain symmetric spaces $X = G(\mathbb{R})/K_\infty$ and we have the cohomology groups $H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})$, they are finitely generated $\mathbb{Z}$ modules. Again we can define an action of the Hecke algebra $\mathcal{H}_\Gamma$ and this Hecke algebra acts semi simply on the inner cohomology $H^\bullet_!(\Gamma\backslash X, \tilde{\mathcal{M}}_\mathbb{Q})$. (theorem 2) Again this Hecke algebra is the tensor product of local Hecke algebras where for almost all primes these local Hecke algebras $\mathcal{H}_p$ are polynomial rings in a certain number of variables. Then the theorem 3 is also valid in this situation. We resume this theme in Chap.III.

$\boxed{\text{HEOP}}$

3.3 Explicit formulas for the Hecke operators, a general strategy.

In the following section we discuss the Hecke operators and for numerical experiments it is useful to have an explicit procedure to compute them in a given case. The main obstruction to get such an explicit procedure is to find an explicit way to compute the arrow $j^\bullet(\alpha)$ in the top line of the diagram (3.1). (we change notation $j(\alpha)$ to $m(\alpha)$).

Let us assume that we have computed the cohomology groups on both sides by means of orbiconvex coverings $\mathfrak{V} : \cup_{i\in I} V_{y_i} = \Gamma(\alpha^{-1})\backslash X$ and $\mathfrak{U} : \cup_{j\in J} U_{y_j} = \Gamma(\alpha)\backslash X$.

The map $m(\alpha)$ is an isomorphism between spaces and hence $m(\alpha)(\mathfrak{V})$ is an acyclic covering of $\Gamma(\alpha)\backslash X$. This induces an identification

$$C^\bullet(\mathfrak{V}, \tilde{\mathcal{M}}) = C^\bullet(m(\alpha)(\mathfrak{V}), \tilde{\mathcal{M}}^{(\alpha)})$$

and the complex on the right hand side computes $H^\bullet(\Gamma(\alpha)\backslash X, \tilde{\mathcal{M}}^{(\alpha)})$. But this cohomology is also computable from the complex $C^\bullet(\mathfrak{U}, \tilde{\mathcal{M}}^{(\alpha)})$. We take the disjoint union of the two indexing sets $I \cup J$ and look at the covering $m_\alpha(\mathfrak{V}) \cup \mathfrak{U}$. (To be precise: We consider the disjoint union $\tilde{I} = I \cup J$ and define a covering $\mathfrak{W}_\mathfrak{i}$ indexed by $\tilde{I}$. If $i \in \tilde{I}$ then $W_i = m(\alpha)(V_{y_i})$ and if $i \in J$ then we put $W_i = U_{x_i}$. We get a diagram of Czech complexes

$$\begin{array}{ccccc}
\to & \bigoplus_{\underline{i}\in I^q} \tilde{\mathcal{M}}^{(\alpha)}(W_{\underline{i}}) & \to & \bigoplus_{\underline{i}\in I^{q+1}} \tilde{\mathcal{M}}^{(\alpha)}(W_{\underline{i}}) \to \\
 & \uparrow & & \uparrow \\
\to & \bigoplus_{\underline{i}\in \tilde{I}^q} \tilde{\mathcal{M}}^{(\alpha)}(W_{\underline{i}}) & \to & \bigoplus_{\underline{i}\in \tilde{I}^{q+1}} \tilde{\mathcal{M}}^{(\alpha)}(W_{\underline{i}}) \to \\
 & \downarrow & & \downarrow \\
\to & \bigoplus_{\underline{i}\in J^q} \tilde{\mathcal{M}}^{(\alpha)}(W_{\underline{i}}) & \to & \bigoplus_{\underline{i}\in J^{q+1}} \tilde{\mathcal{M}}^{(\alpha)}(W_{\underline{i}}) \to
\end{array} \tag{3.1}$$

The sets $I^\bullet, J^\bullet$ are subsets of $\tilde{I}^\bullet$ and the up- and down-arrows are the resulting projection maps. We know that these up- and down-arrows induce isomorphisms in cohomology.

Hence we can start from a cohomology class $\xi \in H^q(\Gamma(\alpha)\backslash X, \tilde{\mathcal{M}}^{(\alpha)})$, we represent it by a cocycle

$$c_\xi \in \bigoplus_{\underline{i}\in I^q} \tilde{\mathcal{M}}^{(\alpha)}(W_{\underline{i}}).$$

Then we can find a cocycle $\tilde{c}_\xi \in \bigoplus_{\underline{i}\in \tilde{I}^q} \tilde{\mathcal{M}}^{(\alpha)}(W_{\underline{i}})$ which maps to c_ξ under the uparrow. To get this cocycle we have to do the following: our cocycle c_ξ is an array with components $c_\xi(\underline{i})$ for $\underline{i} \in I^q$. We have $d_q(c_\xi) = 0$. To get $\tilde{c}_\xi$ we have to give the values $\tilde{c}_\xi(\underline{i})$ for all $\underline{i} \in \tilde{I}^q \setminus I^q$. We must have

$$d_q\tilde{c}_\xi = 0.$$

this yields a system of linear equations for the remaining entries. We know that this system of equations has a solution -this is then our $\tilde{c}_\xi$ - and this solution is unique up to a boundary $d_{q-1}(\xi')$. Then we apply the downarrow to $\tilde{c}_\xi$ and get a cocycle $c_\xi^\dagger$, which represents the same class ξ but this class is now represented by a cocycle with respect to the covering $\mathfrak{U}$. We apply the map $\tilde{u}^\alpha : \tilde{\mathcal{M}}^{(\alpha)} \to \tilde{\mathcal{M}}$ to this cocycle and then we get a cocycle which represents the image of our class ξ under T_α.

3.3.1 Hecke operators for Gl_2:

We consider the classical case. Our group $G/\mathbb{Q}$ is the group $\mathrm{Gl}_2/\mathbb{Q}$ and $K = SO(2) \subset G_\infty$. Then $X = G_\infty/K$ is the union of an upper and a lower half plane. We choose $\tilde{\Gamma} = \mathrm{Gl}_2(\mathbb{Z})$, then

$$\tilde{\Gamma}\backslash G_\infty/K = \Gamma\backslash\mathbb{H},$$

where $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$ and $\mathbb{H}$ is the upper half plane.

As Γ-modules we consider the $\mathbb{Z}$ –module

$$\mathcal{M}_n = \left\{ \sum_{\nu=0}^{n} a_v X^\nu Y^{n-\nu} \mid a_\nu \in \mathbb{Z} \right\}.$$

The group Γ acts by

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} X^\nu Y^{n-\nu} = (aX + cY)^\nu (bX + dY)^{n-\nu}.$$

We observe that the associated sheaf $\mathcal{M}_n$ becomes trivial if $n \not\equiv 0 \mod 2$ hence we assume that n is even. We define a rational representation of $\mathrm{Gl}_2(\mathbb{Q})$ on $\mathcal{M}_{n,\mathbb{Q}}$, which we choose to be

$$\alpha \cdot P(X,Y) = \begin{pmatrix} a & b \\ c & d \end{pmatrix} P(X,Y) = P(aX + cY, bX + dY) \det \begin{pmatrix} a & b \\ c & d \end{pmatrix}^{-n/2}.$$

Here we may also multiply by another power $\det \begin{pmatrix} a & b \\ c & d \end{pmatrix}^m$ of the determinant factor. We call the resulting module $\mathcal{M}_{n,\mathbb{Q}}[m]$, later it will turn out that $m = -n$ is the optimal choice. At this present moment our module is $\mathcal{M}_{n,\mathbb{Q}}[-n/2]$, this choice of the exponent m has the advantage that the center acts trivially.

We refer to Chap.II 2.1.3. We have the two open sets $\tilde{U}_{\mathbf{i}}$, resp. $\tilde{U}_\rho \subset \mathbb{H}$, they are fixed under

$$S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \text{ and } R = \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix},$$

respectively. We also will use the elements

$$T_+ = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}, \; S_1^+ = T_- S T_-^{-1} = \begin{pmatrix} -1 & 1 \\ -2 & 1 \end{pmatrix} \in \Gamma_0^+(2)$$
$$T_- = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}, \; S_1^- = T_+ S T_+^{-1} = \begin{pmatrix} -1 & 2 \\ -1 & 1 \end{pmatrix} \in \Gamma_0^-(2)$$

The elements S_1^+ and S_1^- are elements of order four, i.e. $(S_1^+)^2 = (S_1^-)^2 = -\mathrm{Id}$, the corresponding fixed points are $\frac{\mathbf{i}+1}{2}$ and $\mathbf{i}+1$ respectively. Hence S_1^- fixes the sets $\alpha\tilde{U}_{\frac{\mathbf{i}+1}{2}}$ and $\tilde{U}_{\mathbf{i}+1}$, this is the only occurrence of a non trivial stabilizer.

3.3.2 The special case Sl_2

Let $\pi_1 : \mathbb{H} \to \Gamma\backslash\mathbb{H}$ be the projection. We get a covering $\Gamma\backslash\mathbb{H} = \pi_1(\tilde{U}_{\mathbf{i}}) \cup \pi_1(\tilde{U}_\rho) = U_i \cap U_\rho$. From this covering we get the Czech complex

$$\begin{array}{ccccc} 0 \to & \tilde{\mathcal{M}}(U_{\mathbf{i}}) \oplus \tilde{\mathcal{M}}(U_\rho) & \to & \tilde{\mathcal{M}}(U_{\mathbf{i}} \cap U_\rho) & \to 0 \\ & \downarrow ev_{\tilde{U}_{\mathbf{i}}} \oplus ev_{\tilde{U}_\rho} & & \downarrow ev_{\tilde{U}_{\mathbf{i}} \cap \tilde{U}_\rho} & \\ & \mathcal{M}^{<S>} \oplus \mathcal{M}^{<R>} & \to & \mathcal{M} & \to 0 \end{array} \tag{3.2}$$

and this gives us our formula for the first cohomology

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) = \mathcal{M}/(\mathcal{M}^{<S>} \oplus \mathcal{M}^{<R>}) \tag{3.3}$$

We want to discuss the Hecke operator T_2. To do this we pass to the subgroups

$$\begin{aligned} \Gamma_0^+(2) &= \{\begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid c \equiv 0 \mod 2\} \\ \Gamma_0^-(2) &= \{\begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid b \equiv 0 \mod 2\} \end{aligned} \tag{3.4}$$

we form the two quotients and introduce the projection maps $\pi_2^\pm : \mathbb{H} \to \Gamma_0^\pm(2)\backslash\mathbb{H}$. We have an isomorphism between the spaces

$$\Gamma_0^+(2)\backslash\mathbb{H} \xrightarrow{\alpha_2} \Gamma_0^-(2)\backslash\mathbb{H}$$

which is induced from the map $m_2 : z \mapsto \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix} z = 2z$. This map induces an isomorphism

$$\alpha_2^\bullet : H^1(\Gamma_0^+(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}) \xrightarrow{\sim} H^1(\Gamma_0^-(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}^{(\alpha)}). \tag{3.5}$$

We also have the map between sheaves $u_2 : m \mapsto \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix} m$ and the composition with this map induces a homomorphism in cohomology

$$H^1(\Gamma_0^+(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}) \xrightarrow{u_2^\bullet \circ \alpha_2^\bullet} H^1(\Gamma_0^-(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}). \tag{3.6}$$

This is the homomorphism we need for the computation of the Hecke operator; it is easy to define but it may be difficult in practice to compute it.

3.3.3 The boundary cohomology

It is easier to compute the action of the Hecke operator T_p on the cohomology of the boundary, i. e. to compute the endomorphism

$$T_p : H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}) \to H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}).$$

We know (see 2.29) that $H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}) = \mathcal{M}/(1-T)\mathcal{M}$, we collect some easy facts concerning this module.

For $m \geq 1$ we define the submodules

$$\mathcal{M}^{(m)} = \mathbb{Z}Y^{n-m}X^m \oplus \mathbb{Z}Y^{n-m-1}X^{m+1} \oplus \cdots \oplus \mathbb{Z}X^n,$$

these modules are invariant under the action of T we have $(1-T)\mathcal{M}^{(m)} \subset \mathcal{M}^{(m+1)}$, and $\mathcal{M}^{(m)}/\mathcal{M}^{(m+1)} \xrightarrow{\sim} \mathbb{Z}$. The map $(1-T)$ induces a map

$$\partial_m : \mathcal{M}^{(m)}/\mathcal{M}^{(m+1)} \to \mathcal{M}^{(m+1)}/\mathcal{M}^{(m+2)}$$

which is given by multiplication with $n-m$. Hence it is clear that

$$\mathcal{M}/(1-T)\mathcal{M} = \mathbb{Z}[Y^n] \oplus \mathcal{M}^{(1)}/(1-T)\mathcal{M}$$

and the second summand is a finite module.

The filtration of $\mathcal{M}$ by the $\mathcal{M}^{(m)}$ induces a filtration $H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}})$, we put

$$H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}})^{(m)} := \mathrm{Im}(H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}^{(m)}) \to H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}) \tag{3.7}$$

Then $\boxed{\text{pn1}}$

Proposition 3.3.1. *The quotient*

$$H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}})^{(m)}/H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}})^{(m)+1} \xrightarrow{\sim} \mathbb{Z}/(n-m)\mathbb{Z}$$

The Hecke operator T_p acts on $H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}})^{(m)}/H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}})^{(m)+1}$ by multiplication with $p^{m+1}+p^{n-m}$. Especially we have

$$T_p[Y^n] = (p^{n+1}+1)[Yn]$$

Proof. Postponed ☐

-

Each of the spaces $\Gamma_0^+(2)\backslash\mathbb{H}, \Gamma_0^-(2)\backslash\mathbb{H}$ has two cusps which can be represented by the points $\infty, 0 \in \mathbb{P}^1(\mathbb{Q})$. The stabilizers of these two cusps in $\Gamma_0^+(2)$ resp. $\Gamma_0^-(2)$ are

$$< T_+ > \times\{\pm\mathrm{Id}\} \text{ and } < T_-^2 > \times\{\pm\mathrm{Id}\} \subset \Gamma_0^+(2)$$

resp.

$$< T_+^2 > \times\{\pm\mathrm{Id}\} \text{ and } < T_- > \times\{\pm\mathrm{Id}\} \subset \Gamma_0^-(2)$$

the factor $\{\pm\mathrm{Id}\}$ can be ignored. Then we get

We know that

$$H^1(\partial(\Gamma_0^+(2)\backslash\mathbb{H}), \tilde{\mathcal{M}}) \xrightarrow{\sim} \mathcal{M}/(\mathrm{Id} - T_+)\mathcal{M} \oplus \mathcal{M}/(\mathrm{Id} - T_-^2)\mathcal{M}$$

$$H^1(\partial(\Gamma_0^-(2)\backslash\mathbb{H}), \tilde{\mathcal{M}}) \xrightarrow{\sim} \mathcal{M}/(\mathrm{Id} - T_+^2)\mathcal{M} \oplus \mathcal{M}/(\mathrm{Id} - T_-)\mathcal{M}.$$

But now it is obvious that α maps the cusp ∞ to ∞ and 0 to 0 and then it is also clear that for the boundary cohomology the map

$$\alpha_2^\bullet : \mathcal{M}/(\mathrm{Id} - T_+)\mathcal{M} \oplus \mathcal{M}/(\mathrm{Id} - T_-^2)\mathcal{M} \to \mathcal{M}/(\mathrm{Id} - T_+^2)\mathcal{M} \oplus \mathcal{M}/(\mathrm{Id} - T_-)\mathcal{M}$$

is simply the map which is induced by $u_2 : \mathcal{M} \to \mathcal{M}$. If we ignore torsion then the individual summands are infinite cyclic.

Our module $\mathcal{M}$ is the module of homogenous polynomials of degree n in 2 variables X, Y with integer coefficients. Then the classes $[Y^n], [X^n]$ of the polynomials Y^n (resp.) X^n are generators of $(\mathcal{M}/(\mathrm{Id}-T_+^\nu)\mathcal{M})/\mathrm{tors}$ resp. $(\mathcal{M}/(\mathrm{Id}-T_+^\nu)\mathcal{M})/\mathrm{tors}$ where $\nu = 1$ resp. 2. Then we get for the homomorphism $\alpha_2^\bullet$

$$\alpha_2^\bullet : [Y^n] \mapsto [Y^n], \alpha_2^\bullet : [X^n] \mapsto 2^n[X^n]. \tag{3.8}$$

3.3.4 The explicit description of the cohomology

We give the explicit description of the cohomology $H^1(\Gamma_0^+(2)\backslash\mathbb{H}, \tilde{\mathcal{M}})$. We introduce the projections

$$\mathbb{H} \xrightarrow{\pi_2^+} \Gamma_0^+(2)\backslash\mathbb{H};\ \mathbb{H} \xrightarrow{\pi_2^-} \Gamma_0^-(2)\backslash\mathbb{H}$$

and get the covering $\mathfrak{U}_2$

$$\Gamma_0^+(2)\backslash\mathbb{H} = \pi_2^+(\tilde{U}_{\mathbf{i}}) \cup \pi_2^+(T_-\tilde{U}_{\mathbf{i}}) \cup \pi_2^+(\tilde{U}_\rho) = \pi_2^+(\tilde{U}_{\mathbf{i}}) \cup \pi_2^+(\tilde{U}_{\frac{\mathbf{i}+1}{2}}) \cup \pi_2^+(\tilde{U}_\rho)$$

where we put $T_-\tilde{U}_{\mathbf{i}} = \tilde{U}_{\frac{\mathbf{i}+1}{2}}$. Our set $\{x_\nu\}$ of indexing points is $\mathbf{i}, \frac{\mathbf{i}+1}{2}, \rho$, we put $U_{x_i}^+ = \pi_2^+(\tilde{U}_{x_i})$. Note $T_- \not\in \Gamma_0^+(2), T_+ \in \Gamma_0^+(2)$.

Again the cohomology is computed by the complex

$$0 \to \tilde{\mathcal{M}}(U_{\mathbf{i}}^+) \oplus \tilde{\mathcal{M}}(T_-\tilde{U}_{\mathbf{i}}^+) \oplus \tilde{\mathcal{M}}(U_\rho^+) \to \tilde{\mathcal{M}}(U_{\mathbf{i}}^+ \cap U_\rho^+) \oplus \tilde{\mathcal{M}}(T_-\tilde{U}_{\mathbf{i}}^+ \cap U_\rho^+) \to 0$$

we have to identify the terms as submodules of some $\bigoplus \mathcal{M}$ and write down the boundary map explicitly. We have

$$\begin{array}{ccc}
\tilde{\mathcal{M}}(U_{\mathbf{i}}^+)\oplus\tilde{\mathcal{M}}(U^+_{\frac{\mathbf{i}+1}{2}})\oplus\tilde{\mathcal{M}}(U^+_\rho) & \xrightarrow{d_0} & \tilde{\mathcal{M}}(U_i^+\cap U_\rho^+)\oplus\tilde{\mathcal{M}}(U^+_{\frac{\mathbf{i}+1}{2}}\cap U^+_\rho)\\
\downarrow ev_{\tilde{U}_\mathbf{i}}\oplus ev_{T_-\tilde{U}_\mathbf{i}}\oplus ev_{\tilde{U}_\rho} & & \downarrow ev_{\tilde{U}_\mathbf{i}\cap\tilde{U}_\rho}\oplus ev_{\tilde{U}_\mathbf{i}\cap T_+^{-1}\tilde{U}_\rho}\oplus ev_{T_-\tilde{U}_\mathbf{i}\cap\tilde{U}_\rho}\\
\mathcal{M}\oplus\mathcal{M}^{<S_1^+>}\oplus\mathcal{M} & \xrightarrow{\bar{d}_0} & \mathcal{M}\oplus\mathcal{M}\oplus\mathcal{M}
\end{array} \tag{3.9}$$

where the vertical arrows are isomorphisms. The boundary map $\bar{d}_0$ in the bottom row is given by

$$(m_1,m_2,m_3)\mapsto(m_1-m_3,m_1-T_+^{-1}m_3,m_1-m_2)=(x,y,z)$$

We may look at the (isomorphic) sub complex where $x=z=0$ and $m_1=m_2=m_3$ then we obtain the complex

$$0\to\mathcal{M}^{<S_1^+>}\to\mathcal{M}\to 0;\ m_2\mapsto m_2-T_+^{-1}m_2$$

which provides an isomorphism

$$H^1(\Gamma_0^+(2)\backslash\mathbb{H},\tilde{\mathcal{M}})\xrightarrow{\sim}\mathcal{M}/(\mathrm{Id}-T_+^{-1})\mathcal{M}^{<S_1^+>}. \tag{3.10}$$

A simple computation shows that the cohomology class represented by the class (x,y,z) is equal to the class represented by $(0,y-x+T_+^{-1}z-z,0)$ we write

$$[(x,y,z)]=[(0,y-x+T_+^{-1}z-z,0)] \tag{3.11}$$

3.3.5 The map to the boundary cohomology

We have the restriction map for the cohomology of the boundary

$$\begin{array}{ccc}
H^1(\Gamma_0^+(2)\backslash\mathbb{H},\tilde{\mathcal{M}}) & \xrightarrow{\sim} & \mathcal{M}/(\mathrm{Id}-T_+^{-1})\mathcal{M}^{<S_1^+>}\\
\downarrow & & r^+\oplus r^-\downarrow\\
H^1(\partial(\Gamma_0^+(2)\backslash\mathbb{H}),\tilde{\mathcal{M}}) & \xrightarrow{\sim} & \mathcal{M}/(\mathrm{Id}-T_+)\mathcal{M}\oplus\mathcal{M}/(\mathrm{Id}-T_-^2)\mathcal{M}
\end{array} \tag{3.12}$$

we give a formula for the second vertical arrow. We represent a class $[m]$ by an element $m\in\mathcal{M}$ and send m to its class in in each the two summands, respectively. This is well defined, for r^+ it is obvious, while for r^- we observe that if $m=x-T_+^{-1}x$ and $S_1^+x=x$ then $m=x-T_+^{-1}S_1^+x=x-T_-^2x$.

Restriction and Corestriction

Now we have to give explicit formulas for the two maps π^*,π_* in the big diagram on p. 50 in Chap2.pdf. Here we should change notation: The map π in Chap.2 will now be denoted by :

$$\varpi_2^+:\Gamma_0^+(2)\backslash\mathbb{H}\to\Gamma\backslash\mathbb{H} \tag{3.13}$$

We have the two complexes which compute the cohomology $H^1(\Gamma_0^+(2)\backslash\mathbb{H},\tilde{\mathcal{M}})$ and $H^1(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}})$, and we have defined arrows between them. We realized these two complexes explicitly in (3.9) resp. (3.2) and we have

$$\begin{array}{ccc} \tilde{\mathcal{M}}(U_i^+)\oplus\tilde{\mathcal{M}}(U_{\frac{i+1}{2}}^+)\oplus\tilde{\mathcal{M}}(U_\rho^+) & \xrightarrow{d_0} & \tilde{\mathcal{M}}(U_i^+\cap U_\rho^+)\oplus\tilde{\mathcal{M}}(U_{\frac{i+1}{2}}^+\cap U_\rho^+) \\ (\varpi_2^+)^{(0)}\uparrow\downarrow(\varpi_2^+)_{(0)} & & (\varpi_2^+)^{(1)}\uparrow\downarrow(\varpi_2^+)_{(1)} \\ \tilde{\mathcal{M}}(U_i)\oplus\tilde{\mathcal{M}}(U_\rho) & \xrightarrow{d_0} & \tilde{\mathcal{M}}(U_i\cap U_\rho) \end{array} \tag{3.14}$$

and in terms of our explicit realization in diagram (3.9) this gives

$$\begin{array}{ccc} \mathcal{M}\oplus\mathcal{M}^{<S_1>}\oplus\mathcal{M} & \xrightarrow{d_0} & \mathcal{M}\oplus\mathcal{M}\oplus\mathcal{M} \\ (\varpi_2^+)^{(0)}\uparrow\downarrow(\varpi_2^+)_{(0)} & & (\varpi_2^+)^{(1)}\uparrow\downarrow(\varpi_2^+)_{(1)} \\ \mathcal{M}^{<S>}\oplus\mathcal{M}^{<R>} & \xrightarrow{d_0} & \mathcal{M} \end{array} \tag{3.15}$$

Looking at the definitions we find

$$\begin{gathered} (\varpi_2^+)^{(0)}:(m_1,m_2)\mapsto(m_1,T_-m_1,m_2) \\ (\varpi_2^+)_{(0)}:(m_1,m_2,m_3)\mapsto(m_1+Sm_1+T_-^{-1}m_2,(1+R+R^2)m_3) \end{gathered} \tag{3.16}$$

and we check easily that the composition $(\varpi_2^+)_{(0)}\circ(\varpi_2^+)^{(0)}$ is the multiplication by 3 as it should be, since this is the index of $\Gamma_0(2)^+$ in Γ.

For the two arrows in degree one we find

$$\begin{gathered} (\varpi_2^+)^{(1)}:m\mapsto(m,Sm,T_-m) \\ (\varpi_2^+)_{(1)}:(m_1,m_2,m_3)\mapsto(m_1+Sm_2+T_-^{-1}m_3) \end{gathered} \tag{3.17}$$

We apply equation (3.11) and we see that $(\varpi_2^+)^{(1)}(m)$ is represented by

$$[(\varpi_2^+)^{(1)}(m)]=[0,Sm+T_+^{-1}T_-m-m-T_-m,0] \tag{3.18}$$

We do the same calculation for $\Gamma_0^-(2)$. As before we start from a covering

$$\Gamma_0^-(2)\backslash\mathbb{H}=\pi_2^-(\tilde{U}_{\mathbf{i}})\cup\pi_2^-(T_+\tilde{U}_{\mathbf{i}})\cup\pi_2^-(\tilde{U}_\rho)=\pi_2^-(\tilde{U}_{\mathbf{i}})\cup\pi_2^-(\tilde{U}_{i+1})\cup\pi_2^-(\tilde{U}_\rho)$$

and as before we put $U_{y_\nu}^-=\pi_2^-(\tilde{U}_{y_\nu})$. In this case $\tilde{U}_{i+1}=T_+\tilde{U}_i$ is fixed by $S_1^-=\begin{pmatrix}-1&2\\-1&1\end{pmatrix}\in\Gamma_0^-(2)$ and we get a diagram for the Czech complex

$$\begin{array}{ccc} \tilde{\mathcal{M}}(U_{\mathbf{i}}^-)\oplus\tilde{\mathcal{M}}(U_{\mathbf{i}+1}^-)\oplus\tilde{\mathcal{M}}(U_\rho^-) & \xrightarrow{d_0} & \tilde{\mathcal{M}}(U_{\mathbf{i}}^-\cap U_\rho^-)\oplus\tilde{\mathcal{M}}(U_{\mathbf{i}+1}^-\cap U_\rho^-) \\ ev_{\tilde{U}_{\mathbf{i}}}\oplus ev_{\tilde{U}_{\mathbf{i}+1}}\downarrow\oplus ev_{\tilde{U}_\rho} & & ev_{\tilde{U}_{\mathbf{i}}\cap\tilde{U}_\rho}\oplus ev_{\tilde{U}_{\mathbf{i}}\cap T_-^{-1}\tilde{U}_\rho}\downarrow\oplus ev_{\tilde{U}_{\mathbf{i}+1}\cap\tilde{U}_\rho} \\ \mathcal{M}\oplus\mathcal{M}^{<S_1^->}\oplus\mathcal{M} & \xrightarrow{\bar{d}_0} & \mathcal{M}\oplus\mathcal{M}\oplus\mathcal{M} \end{array} \tag{3.19}$$

Again we can modify this complex and get

$$H^1(\Gamma_0^-(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}) \xrightarrow{\sim} \mathcal{M}/(\mathrm{Id} - T_-^{-1})\mathcal{M}^{<S_1^->}. \tag{3.20}$$

We compute the arrows $(\varpi_2^-)^*, (\varpi_2^-)_*$ in degree one

$$\begin{gathered}(\varpi_2^-)^{(1)} : m \mapsto (m, Sm, T_+m),\\ (\varpi_2^-)_{(1)} : (m_1, m_2, m_3) \mapsto (m_1 + Sm_2 + T_+^{-1}m_3).\end{gathered} \tag{3.21}$$

The computation of $\alpha_2^\bullet$.

We recall our isomorphism α between the spaces and the resulting isomorphism (9.116). The identity map of the module $\mathcal{M}$ and the isomorphism α on the space identifies the two complexes

$$\begin{array}{ccc}\tilde{\mathcal{M}}(U_{\mathbf{i}}^+) \oplus \tilde{\mathcal{M}}(U_{\frac{\mathbf{i}+1}{2}}^+) \oplus \tilde{\mathcal{M}}(U_\rho^+) & \xrightarrow{d_0} & \tilde{\mathcal{M}}(U_{\mathbf{i}}^+ \cap U_\rho^+) \oplus \tilde{\mathcal{M}}(U_{\frac{\mathbf{i}+1}{2}}^+ \cap U_\rho^+)\\ \tilde{\mathcal{M}}^{(\alpha)}(\alpha(U_{\mathbf{i}}^+)) \oplus \tilde{\mathcal{M}}^{(\alpha)}(\alpha(U_{\frac{\mathbf{i}+1}{2}}^+)) \oplus \tilde{\mathcal{M}}^{(\alpha)}(\alpha(U_\rho^+)) & \xrightarrow{d_0} & \tilde{\mathcal{M}}^{(\alpha)}(\alpha(U_{\mathbf{i}}^+ \cap U_\rho^+)) \oplus \tilde{\mathcal{M}}^{(\alpha)}(\alpha(U_{\frac{\mathbf{i}+1}{2}}^+ \cap U_\rho^+))\end{array} \tag{3.22}$$

and if we consider their explicit realization then this identification is given by the equality of $\mathbb{Z}$ modules $\mathcal{M} = \mathcal{M}^{(\alpha)}$. This equality of complexes expresses the identification (9.116). We can compute the cohomology $H^1(\Gamma_0^-(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}^{(\alpha)})$ from any of the two coverings

$$\begin{gathered}\Gamma_0^-(2)\backslash\mathbb{H} = \alpha(U_{\mathbf{i}}^+) \cup \alpha(U_{\frac{\mathbf{i}+1}{2}}^+) \cup \alpha(U_\rho^+) = U_{x_1} \cup U_{x_2} \cup U_{x_3}\\ \text{and}\\ \Gamma_0^-(2)\backslash\mathbb{H} = U_{\mathbf{i}}^- \cup U_{\mathbf{i}+1}^- \cup U_\rho^- = U_{x_4} \cup U_{x_5} \cup U_{x_6}.\end{gathered} \tag{3.23}$$

We have to pick a class $\xi \in H^1(\Gamma_0^-(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}^{(\alpha)})$ and represent it by a cocycle

$$c_\xi \in \bigoplus_{1\le i<j\le 3} \tilde{\mathcal{M}}^{(\alpha)}(U_{x_i} \cap U_{x_j})$$

(The cocycle condition is empty since $U_{x_1} \cap U_{x_2} \cap U_{x_3} = \emptyset$.)

Then we have to produce a cocycle

$$c_\xi^\alpha \in \bigoplus_{4\le i<j\le 6} \tilde{\mathcal{M}}^{(\alpha)}(U_{x_i} \cap U_{x_j})$$

which represents the same class.

To get this cocycle we write down the three complexes

$$\begin{array}{ccc}
\bigoplus_{1\le i<j\le 3}\tilde{\mathcal{M}}^{(\alpha)}(U_{x_i}\cap U_{x_j}) & \to & 0\\
\uparrow & & \\
\bigoplus_{1\le i<j\le 6}\tilde{\mathcal{M}}^{(\alpha)}(U_{x_i}\cap U_{x_j}) & \to & \bigoplus_{1\le i<j<k\le 6}\tilde{\mathcal{M}}^{(\alpha)}(U_{x_i}\cap U_{x_j}\cap U_{x_k})\\
\downarrow & & \\
\bigoplus_{4\le i<j\le 6}\tilde{\mathcal{M}}^{(\alpha)}(U_{x_i}\cap U_{x_j}) & \to & 0
\end{array} \tag{3.24}$$

for our cocycle c_ξ we find a cocycle $c_\xi^\dagger$ in the complex in the middle which maps to c_ξ under the upwards arrow and this cocycle is unique up to a coboundary. Then we project it down by the downwards arrow, i.e. we only take its $4\le i<j\le 6$ components, and this is our cocycle $c_\xi^{(\alpha)}$.

We write down these complexes explicitly. For any pair $\underline{i}=(i,j), i<j$ of indices we have to compute the set $\mathcal{F}_{\underline{i}}$. We drew some pictures and from these pictures we get (modulo errors) the following list (of lists):

$$\begin{array}{cccc}
\mathcal{F}_{1,2}=\emptyset & \mathcal{F}_{1,3}=\{\mathrm{Id},T_+^{-2}\} & \mathcal{F}_{1,4}=\{\mathrm{Id}\} & \mathcal{F}_{1,5}=\{\mathrm{Id},T_+^{-2}\}\\
\mathcal{F}_{1,6}:=\{\mathrm{Id},T_-^{-1}\} & \mathcal{F}_{2,3}=\{\mathrm{Id}\} & \mathcal{F}_{2,4}=\{\mathrm{Id},T_-\} & \mathcal{F}_{2,5}=\{\mathrm{Id}\}\\
\mathcal{F}_{2,6}=\{\mathrm{Id}\} & \mathcal{F}_{3,4}=\{\mathrm{Id},T_+^{2}\} & \mathcal{F}_{3,5}=\{\mathrm{Id}\} & \mathcal{F}_{3,6}=\{\mathrm{Id},S_1^-\}\\
\mathcal{F}_{4,5}=\emptyset & \mathcal{F}_{4,6}=\{\mathrm{Id},T_-^{-1}\} & \mathcal{F}_{5,6}=\{\mathrm{Id}\} &
\end{array} \tag{3.25}$$

Now we have to follow the rules in the first section and we can write down an explicit version of the diagram (3.24) . Here we have to be very careful, because the sets $\tilde U_{\tilde x_2},\tilde U_{\tilde x_5}$ have the non-trivial stabilizer $< S_1^- >$ and we have to keep track of the action of $\Gamma_{\tilde x_{2,5}}$: the set $\mathcal{F}_{i,j}\subset \Gamma_{\tilde x_i}\backslash\Gamma/\Gamma_{\tilde x_j}$. Therefore we have to replace the group elements $\gamma\in\mathcal{F}_{i,j}$ by sets $\Gamma_{\tilde x_i}\gamma\Gamma_{\tilde x_j}$. In the list above we have taken representatives.

$$\begin{array}{ccc}
\bigoplus_{1\le i<j\le 3}\bigoplus_{\gamma\in\mathcal{F}_{i,j}}(\mathcal{M}^{(\alpha)})^{\Gamma_{i,j,\gamma}} & \to & 0\\
\uparrow & & \\
\bigoplus_{1\le i<j\le 6}\bigoplus_{\gamma\in\mathcal{F}_{i,j}}(\mathcal{M}^{(\alpha)})^{\Gamma_{i,j,\gamma}} & \to & \bigoplus_{1\le i<j<k\le 6}\bigoplus_{\gamma\in\mathcal{F}_{i,j,k}}(\mathcal{M}^{(\alpha)})^{\Gamma_{i,j,k,\gamma}}\\
\downarrow & & \\
\bigoplus_{4\le i<j\le 6}\bigoplus_{\gamma\in\mathcal{F}_{i,j}}(\mathcal{M}^{(\alpha)})^{\Gamma_{i,j,\gamma}} & \to & 0
\end{array} \tag{3.26}$$

Here we have to interpret this diagram. The module $\mathcal{M}^{(\alpha)}$ is equal to $\mathcal{M}$ as an abstract module, but an element $\gamma\in\Gamma_0^-(2)$ acts by the twisted action (See

ChapII, 2.2)

$$m \mapsto \gamma *_\alpha m = \alpha^{-1}\gamma\alpha * m$$

here the $*$ denotes the original action. Hence we have to take the invariants $(\mathcal{M}^{(\alpha)})^{\Gamma_{i,j,\gamma}}$ with respect to this twisted action. In our special situation this has very little effect since almost all the $\Gamma_{i,j,\gamma}$ are trivial, except for the intersection $\alpha(\tilde{U}_{\frac{\mathbf{i}+1}{2}}) \cap \tilde{U}_{\mathbf{i}}$ in which case $\Gamma_{i,j,\gamma} =< S_1^- >$. Hence

$$(\mathcal{M}^{(\alpha)})^{<S_1^->} = \mathcal{M}^{<S_1^+>}.$$

Each of the complexes in (3.26) compute the cohomology group $H^1(\Gamma_0^-(2)\backslash\mathbb{H}, \tilde{\mathcal{M}})$ and the diagram gives us a formula for the isomorphism in (9.116). To get $u_\alpha^\bullet$ in (9.116) we apply the multiplication $m_2{:}m \mapsto \alpha m$ to the complex in the middle and the bottom. Then the cocycle c_ξ^α is now an element in $\bigoplus \tilde{\mathcal{M}}^{(\alpha)}$ and αc_ξ^α represents the cohomology class $u_\alpha^\bullet(\xi) \in H^1(\Gamma_0^-(2)\backslash\mathbb{H}, \tilde{\mathcal{M}})$.

Now it is clear how we can compute the Hecke operator

$$T_2 = T_{\begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix}} : \mathcal{M}/(\mathcal{M}^{<S>} \oplus \mathcal{M}^{<R>}) \to \mathcal{M}/(\mathcal{M}^{<S>} \oplus \mathcal{M}^{<R>})$$

We pick a representative $m \in \mathcal{M}$ of the cohomology class. We apply $(\varpi_2^+)^{(1)}$ in the diagram (3.15) to it and this gives the element $(Sm, m, T_- m) = c_\xi$. We apply the above process to compute $c_\xi^{(\alpha)}$. Then $\alpha c_\xi^{(\alpha)} = (m_1, m_2, m_3)$ is an element in $\tilde{\mathcal{M}}(U_{\mathbf{i}}^- \cap U_\rho^-) \oplus \tilde{\mathcal{M}}(U_{\mathbf{i}+1}^- \cap U_\rho^-)$ and this module is identified with $\mathcal{M} \oplus \mathcal{M} \oplus \mathcal{M}$ by the vertical arrow in (3.19). To this element we apply the trace

$$(\varpi_2^-)_{(1)}(m_1, m_2, m_3) = m_1 + m_2 + T_+^{-1} m_3$$

and the latter element in $\mathcal{M}$ represents the class $T_2([m])$.

We have written a computer program which for a given $\mathcal{M} = \mathcal{M}_n$, i.e. for a given even positive integer n, computes the module $H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})$ and the endomorphism T_2 on it.

Looking our data we discovered the following (surprising?) fact: We consider the isomorphism in equation (9.116). We have the explicit description of the cohomology in (3.10)

$$H^1(\Gamma_0^+(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}) \xrightarrow{\sim} \mathcal{M}/(\mathrm{Id} - T_+^{-1})\mathcal{M}^{<S_1^+>}$$

and

$$H^1(\Gamma_0^-(2)\backslash\mathbb{H}, \tilde{\mathcal{M}}^{(\alpha)}) \xrightarrow{\sim} \mathcal{M}/(\mathrm{Id} - T_-^{-1})(\mathcal{M}^{(\alpha)})^{<S_1^->}$$

We know that we may represent any cohomology class by a cocycle

$$c_\xi = (0, c_\xi, 0) \in \mathcal{M}^{(\alpha)}(\pi_2^-(\alpha(U_{\mathbf{i}}) \cap \alpha(U_\rho)) \oplus \mathcal{M}^{(\alpha)}(\pi_2^-(\alpha(U_{\mathbf{i}}) \cap \alpha(T_+^{-1} U_\rho)) \oplus \mathcal{M}^{(\alpha)}(\pi_2^-(\alpha(U_{\frac{\mathbf{i}+1}{2}}) \cap \alpha(T_+^{-1} U_\rho))$$

so it is non zero only in the middle component and then it is simply an element in $\mathcal{M}$. If we now look at our data, then it seems to by so that $c_\xi^{(\alpha)}$ is also non zero only in the middle, hence

$$c_\xi^{(\alpha)} \in (0, c'_\xi, 0) \in 0 \oplus \mathcal{M}^{(\alpha)}(\pi_2^-(U_{\mathbf{i}} \cap T_-^{-1} U_\rho)) \oplus 0$$

hence it is also in $\mathcal{M}^{(\alpha)}$ and then our data seem to suggest that

$$c'_\xi = c_\xi$$

Hence we see that the homomorphism in equation (8.46) is simply given by

$$X^\nu Y^{n-\nu} \mapsto 2^\nu X^\nu Y^{n-\nu}.$$

Is there a kind of homotopy argument (- 2 moves continuously to 1)-, which explains this?

We get an explicit formula for the Hecke operator T_2 : We pick an element $m \in \mathcal{M}$ representing the class $[m]$. We send it by $(\varpi_2^+)^{(1)}$ to $H^1(\Gamma_0^+(2)\backslash\mathbb{H}, \tilde{\mathcal{M}})$, i.e.

$$(\varpi_2^+)^{(1)} : m \mapsto (m, Sm, T_- m) \tag{3.27}$$

We modify it so that the first and the third entry become zero see(3.11)

$$[(m, Sm, T_- m)] = [(0, Sm - m + T_+^{-1}T_- m - T_- m, 0)] \tag{3.28}$$

To the entry in the middle we apply $M_2 = \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix}$ and then apply $(\varpi_2^-)_{(1)}$ and get

$$T_2([m]) = [S \cdot M_2(Sm - m + T_+^{-1}T_- m - T_- m)] \tag{3.29}$$

3.3.6 The first interesting example

We give an explicit formula for the cohomology in the case of $\mathcal{M} = \mathcal{M}_{10}$. We define the sub-modul

$$\mathcal{M}^{\mathrm{tr}} = \bigoplus_{\nu=0}^{5} \mathbb{Z} Y^{10-\nu} X^\nu$$

and we have the truncation operator

$$\mathrm{trunc} : Y^{10-\nu}X^\nu \mapsto \begin{cases} Y^{10-\nu}X^\nu & \text{if } \nu \leq 5, \\ (-1)^{\nu+1} Y^\nu X^{10-\nu} & \text{else,} \end{cases}$$

which identifies the quotient module $\mathcal{M}/\mathcal{M}^{<S>}$ to $\mathcal{M}^{\mathrm{tr}}$. To get the cohomology we have to divide by the relations coming from $\mathcal{M}^{<R>}$, i.e. we have to divide by the submodule $\mathrm{trunc}(\mathcal{M}^{<R>}$.) The module of these relations is generated by

$$\mathrm{R}_1 = 10Y^9X + 20Y^7X^3 + Y^5X^5$$
$$\mathrm{R}_2 = 9Y^8X^2 - 36Y^7X^3 + 14Y^6X^4 - 45Y^5X^5$$
$$\mathrm{R}_3 = 8Y^7X^3 + 10Y^5X^5$$

and then

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) = \bigoplus_{\nu=0}^{5} \mathbb{Z} Y^{10-\nu}X^\nu / \{\mathrm{R}_1, \mathrm{R}_2, \mathrm{R}_3\} \tag{3.30}$$

We simplify the notation and put $e_\nu = Y^\nu X^{n-\nu}$. Using R_1 we can eliminate $e_5 = -10e_9 - 20e_7$ and then

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) = \bigoplus_{\nu=10}^{\nu=6} \mathbb{Z}e_\nu / \{-50e_9 + 9e_8 - 96e_7 + 14e_6, -100e_9 - 192e_7\} \tag{3.31}$$

introduce a new basis $\{f_{10}, f_9, f_8, f_7, f_6, f_5\}$ of the $\mathbb{Z}$ module $\mathcal{M}^{\mathrm{tr}}$:

$$\begin{aligned} f_{10} = e_{10}; f_8 = -2e_8 - 3e_6; f_6 = 9e_8 + 14e_6 \\ f_9 = -12e_9 - 23e_7; f_7 = 25e_9 + 48e_7; f_5 = 10e_9 + 20e_7 + e_5 \end{aligned} \tag{3.32}$$

and hence in the quotient we get $\bar{f}_5 = 0$ and $2\bar{f}_7 = \bar{f}_6$ and therefore

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) = \mathbb{Z}\bar{f}_{10} \oplus \mathbb{Z}\bar{f}_9 \oplus \mathbb{Z}\bar{f}_8 \oplus \mathbb{Z}/(4)\bar{f}_7 \tag{3.33}$$

(If we invert the primes < 12 then we we can work with e_{10}, e_9, e_8 and in cohomology $e_6 = -\frac{9}{14}e_8, e_5 = \frac{5}{12}e_9, e_7 = -\frac{25}{48}e_9$.)

If we can apply the above procedure to compute the action of T_2 on cohomology we get the following matrix for T_2 :

$$T_2 = \begin{pmatrix} 2049 & -68040 & 0 & 0 \\ 0 & -24 & 0 & 0 \\ 0 & 0 & -24 & 0 \\ 0 & 0 & 0 & 2 \end{pmatrix} \tag{3.34}$$

Hence we see that it is non trivial on the torsion subgroup. If we divide by the torsion then the matrix reduces to a (3,3)-matrix and this matrix gives us the endomorphism on the "integral" cohomology which is defined in generality by

$$H^\bullet_{\mathrm{int}}(\Gamma\backslash X, \tilde{\mathcal{M}}) = H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}})/\mathrm{tors} \subset H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}}_{\mathbb{Q}}) \tag{3.35}$$

here we should be careful: the functor $H^\bullet \to H^\bullet_{\mathrm{int}}$ is not exact. In our case we get (perhaps up to a little piece of 2-torsion) exact sequences of Hecke modules

$$\begin{array}{ccccccccc} 0 & \to & \mathbb{Z}f_9 \oplus \mathbb{Z}f_8 & \to & \mathbb{Z}f_{10} \oplus \mathbb{Z}f_9 \oplus \mathbb{Z}f_8 & \xrightarrow{r} & \mathbb{Z}\bar{f}_{10} & \to & 0 \\ & & \| & & \| & & \| & & \\ 0 & \to & H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) & \to & H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) & \xrightarrow{r} & H^1_{\mathrm{int},!}(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}) & \to & 0 \end{array} \tag{3.36}$$

where $T_2(\bar{f}_{10}) = (2^{11}+1)\bar{f}_{10}$. If we tensor by $\mathbb{Q}$ then we can find an element (the Eisenstein class) $f_{10}^\dagger \in H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) \otimes \mathbb{Q}$ which maps to $\bar{f}_{10}$ This element is not necessarily integral, in our case an easy computation shows that $691f^\dagger \in H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})$. This means that 691 is the denominator of $f_{10}^\dagger$, i.e. 691 is the *denominator* of the Eisenstein class $f_{10}^\dagger$.

The exact sequence $\mathcal{X}_{10}$ in (3.36) is an exact sequence of modules for the Hecke algebra $\mathcal{H} \supset \mathbb{Z}[T_2]$ and hence it yields an element

$$[\mathcal{X}_{10}] \in \mathrm{Ext}^1_{\mathcal{H}}(\mathbb{Z}f_{10}, H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})), \tag{3.37}$$

and an easy calculation shows that this Ext^1 group is cyclic of order 691 and that it is generated by $\mathcal{X}_{10}$.

We can go one step further and reduce mod 691. Since there is at most 2 torsion we get an exact sequence of Hecke-modules

$$0 \to \quad H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{F}_{691}) \to H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{F}_{691}) \xrightarrow{r} \quad H^1_{\mathrm{int},!}(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}} \otimes \mathbb{F}_{691}) \to 0. \tag{3.38}$$

The matrix giving the Hecke operator mod 691 becomes

$$T_2 = \begin{pmatrix} 667 & 369 & 0 \\ 0 & 667 & 0 \\ 0 & 0 & 667 \end{pmatrix} \tag{3.39}$$

This implies that the extension class $[\mathcal{X}_{10} \otimes \mathbb{F}_{691}]$ is a element of order 691. This implies that 691 divides the order of $[\mathcal{X}_{10}]$ and hence divides the order of the denominator of the Eisenstein class.

The general case

Now we describe the general case $\mathcal{M} = \mathcal{M}_n$ where n is an even integer. We define $\mathcal{M}^{\mathrm{tr}}$ as above, if $n/2$ is even, then we leave out the summand $X^{n/2}Y^{n/2}$, we get

$$\mathcal{M}^{\mathrm{tr}} = \mathcal{M}/\mathcal{M}^{<S>}.$$

This gives us for the cohomology and the restriction to the boundary cohomology

$$\begin{array}{ccc} H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) & \xrightarrow{\sim} & \mathcal{M}^{\mathrm{tr}}/\mathrm{Rel} \\ \downarrow & & \downarrow \\ H^1(\partial(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) & \xrightarrow{\sim} & \mathcal{M}/(\mathrm{Id}-T)\mathcal{M}. \end{array} \tag{3.40}$$

We have the basis

$$e_n = \mathrm{trunc}(Y^n), e_{n-1} = \mathrm{trunc}(Y^{n-1}X), \dots, \begin{cases} Y^{n/2}X^{n/2} & n/2 \text{ odd} \\ 0 & \text{else} \end{cases}$$

for $\mathcal{M}^{\mathrm{tr}}$. Let us put $n_2 = n/2$ or $n/2-1$. Then the algorithm *Smithnormalform* provides a second basis $f_n = e_n, f_{n-1}, \dots, f_{n_2}$ such that the module of relations becomes

$$d_n f_n = 0, d_{n-1}f_{n-1} = 0, \dots, d_t f_t = 0, \dots, d_{n_2} f_{n_2} = 0$$

where $d_{n_2}|d_{n_2+1}|\dots|d_n$. We have $d_n = d_{n-1} = \cdots = d_{n-2s} = 0$ where $2s+1 = \dim H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}) \otimes \mathbb{Q}$ and $d_{n-2s-1} \neq 0$.

With respect to this basis the Hecke operator T_2 is of the form

$$T_2(f_i) = \sum_{j=n}^{j=n_2} t^{(2)}_{i,j} f_j \tag{3.41}$$

where we have (the numeration of the rows and columns is downwards from n to n_2)

$$\begin{gathered} t^{(2)}_{\nu,n} = 0 \text{ for } \nu < n \text{ and } t^{(2)}_{i,j} \in \operatorname{Hom}(\mathbb{Z}/(d_i), \mathbb{Z}(d_j)) \\ \text{and } t^{(2)}_{i,j} = 0 \text{ for } i \geq n-2s, j < n-2s \end{gathered} \tag{3.42}$$

If we divide by the torsion then we get for the restriction map to the boundary cohomology

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})_{\text{int}} = \bigoplus_{\nu=n}^{n-2s} \mathbb{Z}f_\nu \xrightarrow{r} H^1(\partial(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})_{\text{int}} = \mathbb{Z}Y^n \tag{3.43}$$

where $f_n \mapsto Y^n$ and $T_2(Y^n) = (2^{n+1}+1)Y^n$. The Manin-Drinfeld principle implies that we can find a vector (Reference to ????)

$$\text{Eis}_n = f_n + \sum_{\nu=n-1}^{\nu=n-2s} x_\nu f_\nu, \quad x_\nu \in \mathbb{Q} \tag{3.44}$$

which is an eigenvector for T_2 i.e.

$$T_2(\text{Eis}_n) = (2^{n+1}+1)\text{Eis}_n \tag{3.45}$$

The least common multiple $\Delta(n)$ of the denominators of the x_ν is the denominator of the Eisenstein class, it is the smallest positive integer for which

$$\Delta(n)\text{Eis}_n \in H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})_{\text{int}}. \tag{3.46}$$

This denominator is of great interest and our computer program allows us to compute it for any given not to large n. We have to compute the x_ν.

We define $H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})_{\text{int},!}$ to be the kernel of r, this is equal to $\bigoplus_{\nu=n-1}^{n-2s} \mathbb{Z}f_\nu$ and the Hecke operator defines an endomorphism

$$T_2^{\text{cusp}} : H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})_{\text{int},!} \to H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})_{\text{int},!} \tag{3.47}$$

which is given by the matrix $(t^{(2)}_{i,j})$ where $n-1 \geq i, j, n-2s$, i.e. we delete the "first" (i.e.the n-th) row and column.

Now we know that $T_2(f_n) = (2^{n+1}+1)f_n + \sum_{\mu=n-1}^{\mu=n-2s} t^{(2)}_{n,\mu} f_\mu$. Then the x_μ are the unique solution of

$$\sum_{\nu=n-1}^{\nu=n-2s} ((2^{n+1}+1)\delta_{\nu,\mu} - t^{(2)}_{\nu,\mu})x_\nu = t^{(2)}_{n,\mu}; \{\mu = n-1, \dots, n-2s\} \tag{3.48}$$

The denominators of the x_ν are closely related to values of the Riemann ζ function, it seems that

$$\Delta(n) = \text{numerator}(\zeta(-1-n)). \tag{3.49}$$

This has been verified up to $n \leq 150$ by a computer. We found some handwritten notes (from about 1980) where this is actually proved by using modular symbols, but this proof has to be checked again.

3.3.7 Computing $\mod p$

.

Of course the coefficients $t^{(2)}_{\nu,\mu}$ become very large if n becomes larger, hence we can verify (3.49) only in a very small range of degrees n.

But if we are a little bit more modest we may be able check experimentally whether a given - perhaps large- prime p, which divides a numerator$\zeta(-1-n)$ for a very large n actually divides $\Delta(n)$. Here we need a little bit of luck.

Assume that we have such a pair (p,n). We want to show that the prime p divides the lcm of the denominators of the x_ν in (3.48) and this means that the equation (3.48) has no solution in $\mathbb{Z}_{(p)}$, the local ring at p. This is of course clear if the $\mod p$ reduced equation

$$\sum_{\nu=n-1}^{\nu\equiv n-2s} ((2^{n+1}+1)\delta_{\nu,\mu} - t^{(2)}_{\nu,\mu})x_\nu \equiv t^{(2)}_{n,\mu} \mod p \tag{3.50}$$

has no solution. (Of course the converse is not true, therefore we need just a little bit of luck!). In this computation the numbers become much smaller. In fact this has now been checked for all $n \leq 100$ we can can easily go much further.

$\boxed{\text{higher}}$

Higher powers of p

This reasoning can also be applied if we look at higher powers of p dividing a numerator$\zeta(-1-n)$. Let us assume that $p^{\delta_p(n)}|$numerator$\zeta(-1-n)$. We have to show that $p^{\delta_p(n)}$ divides the lcm of the denominators of the x_ν in equation (3.48). This follows if we show that the equation

$$\sum_{\nu=n-1}^{\nu\equiv n-2s} ((2^{n+1}+1)\delta_{\nu,\mu} - t^{(2)}_{\nu,\mu})x_\nu \equiv p^{\delta_p(n)-1} t^{(2)}_{n,\mu} \mod p^{\delta_p(n)} \tag{3.51}$$

has no solution. This in turn means that the class

$$[\mathcal{X}_n \otimes \mathbb{Z}/p^{\delta_p(n)}\mathbb{Z}] \in \mathrm{Ext}^1_{\mathcal{H}}((\mathbb{Z}/p^{\delta_p(n)}\mathbb{Z})(-1-n), H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes (\mathbb{Z}/p^{\delta_p(n)}\mathbb{Z}))$$

has exact order $p^{\delta_p(n)}$.

Interesting cases to check are $p = 37, 59, 67, 101...$ then we have

$$\zeta(-31) \equiv 0 \mod 37;\ \zeta(-283) \equiv 0 \mod 37^2;\ \zeta(-37579) \equiv 0 \mod 37^3;\ \zeta(-1072543) \equiv 0 \mod 37^4; \dots$$

$$\zeta(-43) \equiv 0 \mod 59;\ \zeta(-913) \equiv 0 \mod 59^2$$

Here our computations have a surprising outcome. For $\zeta(-283)$ resp. $\zeta(-913)$ it has been checked that the order of the extension class is 37 resp. 59 so it is smaller than expected. This is not in conflict with the assertion that the denominator is of order $37^2, 59^2$. In fact it turns out that the determinant of the matrix on the left hand side in (3.51) is $(37^3)^2 = 37^6$ where the denominator only predicts 37^4. Is this always so and is this also true for other Hecke operators?

3.3.8 The denominator and the congruences

For the following we assume that (3.49) is correct. We discuss the denominator of the Eisenstein class in this special case. In [Talk-Lille] this is discussed in a more abstract way, so here we treat basically the simplest example of 4.3 in [Talk-Lille]. Remember that in this section $\tilde{\mathcal{M}} = \tilde{\mathcal{M}}_n$, i.e. we have fixed an even positive integer n.

We have the fundamental exact sequence
$\boxed{\text{fuex}}$

$$0 \to H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \to H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \xrightarrow{r} H^1_{\mathrm{int}}(\partial(\Gamma\backslash\mathbb{H}),\tilde{\mathcal{M}}) = \mathbb{Z}e_n \to 0 \tag{3.52}$$

and we know that $T_2(e_n) = (2^{n+1}+1)e_n$. We get a submodule

$$H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \oplus \mathbb{Z}\tilde{e}_n \subset H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \tag{3.53}$$

where $\tilde{e}_n$ is primitive and $T_2\tilde{e}_n = (2^{n+1}+1)\tilde{e}_n$. We have $r(\tilde{e}_n) = \Delta(n)e_n$ and

$$H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}})/(H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \oplus \mathbb{Z}\tilde{e}_n) = \mathbb{Z}/\Delta(n)\mathbb{Z} \tag{3.54}$$

Any $m \in \mathbb{Z}/\Delta(n)\mathbb{Z}$ can be written as

$$m = r(\frac{y' + m\tilde{e}_n}{\Delta(n)}) \tag{3.55}$$

and this yields an inclusion $\mathbb{Z}/\Delta(n)\mathbb{Z} \hookrightarrow H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \otimes \mathbb{Z}/\Delta(n)\mathbb{Z}$.

Hence

Theorem 3.3.1. *The Hecke module $H^1_{\mathrm{int}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \otimes \mathbb{Z}/\Delta(n)\mathbb{Z}$ contains a cyclic submodule $\mathbb{Z}/\Delta(n)\mathbb{Z}(-1-n)$ on which the Hecke operator T_p acts by the eigenvalue $p^{n+1}+1 \mod \Delta(n)$ for all primes p.*

This theorem has interesting consequences which will be discussed in the following.

In section (4.1.3) we will review the famous multiplicity one theorem which follows from the theory of automorphic forms. This theorem implies that we can find a finite normal field extension $F/\mathbb{Q}$ such that $\boxed{\text{decoF}}$

$$H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \otimes F = \bigoplus_{\pi_f} H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}} \otimes F)[\pi_f] \tag{3.56}$$

where π_f runs over a finite set of homomorphisms $\pi_f : \mathcal{H} \to \mathcal{O}_F$, and where $H^1..[\pi_f]$ is the rank 2 eigenspace for π_f. We also have the action of the complex conjugation on the cohomology (See sect. how) and under this action each eigenspace decomposes into a one dimensional + and a one dimensional - eigenspace, i.e. $H^1..[\pi_f] = H^1_+..[\pi_f] \oplus H^1_-..[\pi_f]$. Let us denote the set of $\pi_f : \mathcal{H} \to \mathcal{O}_f$ which occur with positive multiplicity (then 2) in the above decomposition by $\mathrm{Coh}^{(n)}_!$.

Our considerations at the beginning of this section imply that we also have a decomposition of

$$H^1(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \otimes F = H^1_!(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}) \otimes F \oplus Fe_n$$

where $T_p e_n = (p^{n+1}+1)e_n$. Let $\pi_f^{\mathrm{Eis}} : \mathcal{H} \to \mathbb{Z}$ be the homomorphism $\pi_f^{\mathrm{Eis}} : T_p \to p^{n+1}+1$.

This decomposition induces a Jordan-Hölder filtration on the integral cohomology $\boxed{\text{JH}}$

$$(0) \subset \mathcal{JH}^{(1)} H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{\mathcal{O}_F}) \subset \mathcal{JH}^{(2)} H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{\mathcal{O}_F}) \subset \cdots \subset \mathcal{JH}^{(r)} H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{\mathcal{O}_F}) \tag{3.57}$$

where the subquotients a locally free $\mathcal{O}_F$ modules of rank 2 and after tensoring with F they become isomorphic to the different eigenspaces.

We choose a prime p which divides $\Delta(n)$, let $p^{\delta_p(n)} || \Delta(n)$. Let $\mathfrak{p}$ be a prime in $\mathcal{O}_F$ which lies above p. If e_p is the ramification index then we have

$$\{0\} \subset \mathcal{O}_F/\mathfrak{p}^{e_p\delta_p(n)}(-1-n) \subset H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{\mathcal{O}_F}) \otimes \mathcal{O}_F/\mathfrak{p}^{e\delta_p(n)} \tag{3.58}$$

The above Jordan-Hölder filtration induces a Jordan-Hölder filtration on the cohomology $\mod \mathfrak{p}^{e_p\delta_p(n)}$ we have $\boxed{\text{JHmod}}$

$$\{0\} \subset \mathcal{JH}^{(1)} H^1_{\mathrm{int},!}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{\mathcal{O}_F}) \otimes \mathcal{O}_F/\mathfrak{p}^{e_p\delta_p(n)} \hookrightarrow \mathcal{JH}^{(2)} \dots \tag{3.59}$$

where again the subquotients are free $\mathcal{O}_F/\mathfrak{p}^{e_p\delta_p(n)}$ modules of rank 2. A simple argument shows

$\boxed{\text{cong1}}$

Theorem 3.3.2. *We can find $\pi_{f,1}, \pi_{f,2} \dots, \pi_{f,r}$ in the above decomposition and numbers $f_1 > 0, f_2 > 0, \dots, f_r > 0$ such that $\sum f_i = e_p\delta_p(n)$ and we have the congruence*

$$\pi_{f,i}(T_\ell) \equiv \ell^{n+1} + 1 \mod \mathfrak{p}^{f_i} \tag{3.60}$$

for all primes ℓ.

In the following section we look at this theorem from a slightly different point of view.

p-adic coefficients

In the previous section we decomposed the inner cohomology into eigenspaces under the action of the Hecke algebra. In our special situation - the underlying group $G = \mathrm{Gl}_2$- this is also valid for the full cohomology. But our main object of interest is the cohomology with integral coefficients and our example above shows that the cohomology with integral coefficients does not split.

To investigate the structure of the cohomology groups $H^\bullet(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})$ we choose a prime p. This prime will be fixed throughout this section, let $\mathbb{Z}_{(p)} \subset \mathbb{Q}$ be the local ring at p. We are interested in the structure of the cohomology groups $H^\bullet(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_{(p)})$ as modules under the Hecke algebra. But now it is convenient to go still one step further, we tensorize our coefficient systems by $\mathbb{Z}_p$, the ring of p-adic integers. We want to simplify the notation: In this section we denote by $\mathcal{M}_n$ the $\mathbb{Z}_p$-module $\mathcal{M}_\lambda \otimes \mathbb{Z}_p$ where $\lambda = n\gamma + d\det$ where the value of d is irrelevant it just has to have the right parity. (Comment? $\mathbb{Z}_{(p)} \to \mathbb{Z}_p$ is flat hence it does preserve Ext^1 groups.)

Let M be any finitely generated $\mathbb{Z}_p$-module, let $T_p : M \to M$ be an endomorphism. Of course X is a topological module, the open neighborhoods of 0 are the modules $p^r M$. Following Hida we define two submodules

$$M_{\mathrm{ord}} = \bigcap_{r\to\infty} T_p^r M;\; M_{\mathrm{nilpt}} = \{x \in M | T_p^r x \to 0\} \tag{3.61}$$

A simple compactness argument shows that

$$M = M_{\mathrm{ord}} \oplus M_{\mathrm{nilpt}} \tag{3.62}$$

and it is also clear that $M \to M_{\mathrm{ord}}$ is an exact functor.

We apply this to our cohomology groups, and we assume that $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$. We start from the exact sequence of Γ modules

$$0 \to \mathcal{M}_n \xrightarrow{\times p} \mathcal{M}_n \to \mathcal{M}_n \otimes \mathbb{F}_p \to 0. \tag{3.63}$$

Here we want to assume that $p > 3$ then we get the resulting exact sequence of sheaves and hence a long exact sequence of cohomology groups

$$\begin{gathered} 0 \to (\mathcal{M}_n^\Gamma)_{\mathrm{ord}} \xrightarrow{\times p} (\mathcal{M}_n^\Gamma)_{\mathrm{ord}} \to (\mathcal{M}_n \otimes \mathbb{F}_p)_{\mathrm{ord}} \to \\ \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n) \xrightarrow{\times p} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n) \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{F}_p) \to 0 \end{gathered} \tag{3.64}$$

and we can break this sequence into pieces

$$0 \to (\mathcal{M}_n^\Gamma)_{\mathrm{ord}} \xrightarrow{\times p} (\mathcal{M}_n^\Gamma)_{\mathrm{ord}} \to (\mathcal{M}_n \otimes \mathbb{F}_p)^\Gamma_{\mathrm{ord}} \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n)[p] \to 0 \tag{3.65}$$

and

$$0 \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n)[p] \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n) \xrightarrow{\times p} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n) \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{F}_p) \to 0 \tag{3.66}$$

where of course $\dots[p]$ means kernel of the multiplication by p and the far most 0 on the right is the vanishing of H^2.

We analyze these two sequences and get

$\boxed{\text{ordtorfree}}$

Theorem 3.3.3. *The cohomology $H^1_{ord}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n)$ is torsion free unless we have $n > 0$ and $n \equiv 0 \mod p(p-1)$. The cohomology groups $H^1_{c,\ ord}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n)$ are always torsion free and $H^2_{c,\ ord}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n) = 0$*

Proof. We consider the polynomial ring in two variables $\mathbb{F}_p[X, Y]$. On this ring we have the action of $\mathrm{Sl}_2(\mathbb{Z})$. It is an old theorem of L.E. Dickson that the ring of invariants is generated by the two polynomials

$$f_1 = X^pY - XY^p \text{ and } f_2 = \frac{X^{p^2-1} - Y^{p^2-1}}{X^{p-1} - Y^{p-1}} = X^{(p-1)p} + X^{(p-1)(p-1)}Y^{p-1} + \dots \tag{3.67}$$

Now every element in $(\mathcal{M}_n \otimes \mathbb{F}_p)^\Gamma_{\text{ord}}$ is a sum of monomials $f_1^a f_2^b$ where $a(p+1) + bp(p-1) = n$. We see that

$$u_{\begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix}} = u_\alpha : \mathcal{M}_n^{(\alpha)} \to \mathcal{M}_n$$

multiplies f_1 with a multiple of p and hence we see that all the monomials with $a > 0$ are multiplied by a multiple of p. This means that $(\mathcal{M}_n \otimes \mathbb{F}_p)^\Gamma_{\text{ord}} \neq 0$ if and only if $n = bp(p-1)$. If $n = 0$ we the map $\mathcal{M}_n^\Gamma = \mathbb{Z}_p \to (\mathcal{M}_n \otimes \mathbb{F}_p)^\Gamma$ is surjective if $n > 0$ we have $\mathcal{M}_n^\Gamma = 0$ and hence the theorem.

For the assertions concerning the compactly supported cohomology we have to recall that $H^2_c(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n) = (\mathcal{M}_n)_\Gamma = \mathcal{M}_n / I_\Gamma \mathcal{M}_n$ [book vol I, section 2 and 4.8.5]. We check easily that $X^n, Y^n \in I_\Gamma \mathcal{M}_n$ and the assertion is clear. $\square$

We write $n = n_0 + (p-1)\alpha$ where we assume $0 < n_0 < p-1$, we know that

$$H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n) \otimes \mathbb{Z}/p^r\mathbb{Z} \xrightarrow{\sim} H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{Z}/p^r) \tag{3.68}$$

we have a second theorem

$\boxed{\text{interpol}}$

Theorem 3.3.4. *If $n = n_0 + (p-1)\alpha, n' = n_0 + (p-1)\alpha'$ and $\alpha \equiv \alpha' \mod p^{r-1}$, (i.e. $n \equiv n' \mod (p-1)p^{r-1}$) then we have a canonical Hecke invariant isomorphism*

$$\Phi(n,n')_r : H^1_{ord}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{Z}/p^r) \xrightarrow{\sim} H^1_{ord}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n'} \otimes \mathbb{Z}/p^r). \tag{3.69}$$

This system of isomorphisms is consistent with change of the parameter α, α' and r.

Proof. See paper on interpolation. $\square$

We find a finite extension $F/\mathbb{Q}_p$ such that we have a decomposition into eigenspaces

$$H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes F) = \bigoplus_{\pi_f} H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes F)[\pi_f] \oplus Fe_n \tag{3.70}$$

where the first summation goes over those $\pi_f \in \text{Coh}_!^{(n)}$ for which $\pi_f(T_p)$ is a unit in $\mathcal{O}_\mathfrak{p}$, the ring of integers in F. Let us denote this set by $\text{Coh}^{(n)}_{!,\text{ord}}$. Then the full summation goes over the set $\text{Coh}^{(n)}_{\text{ord}} = \text{Coh}^{(n)}_{!,\text{ord}} \cup \{\pi_f^{\text{Eis}}\}$. Intersecting this decomposition with $H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathcal{O}_\mathfrak{p})$ gives us a submodule of finite index

$$H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathcal{O}_\mathfrak{p}) \supset \bigoplus_{\pi_f} H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathcal{O}_\mathfrak{p})[\pi_f] \oplus \mathcal{O}_\mathfrak{p} e_n \tag{3.71}$$

and this also gives us a Jordan-Hölder filtration as in (3.57).

We consider the reduction maps

$\boxed{\text{redukdiag}}$

$$\begin{array}{ccc} H^1_{!,\,\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathcal{O}_\mathfrak{p}) & \to & H^1_{!,\,\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{F}(\mathfrak{p})) \\ \downarrow & & \downarrow \\ H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathcal{O}_\mathfrak{p}) & \to & H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{F}(\mathfrak{p})) \end{array} \tag{3.72}$$

the right hand sides do not depend on α. Any $\pi_f \in \mathrm{Coh}^{(n)}_{\mathrm{ord}}$ we get a non zero homomorphism $\bar\pi_f = \pi_f \times \mathbb{F}(\mathfrak{p}) : \mathcal{H} \to \mathbb{F}(\mathfrak{p})$. The map $\pi_f \to \bar\pi_f$ is not necessarily injective: we say that $\pi_{1,f}$ and $\pi_{2,f}$ are congruent $\mod \mathfrak{p}$ if $\pi_{1,f}(T_\ell) \equiv \pi_{2,f}(T_\ell)$ $\mod \mathfrak{p}$ for all primes ℓ, or in other words $\bar\pi_{1,f} = \bar\pi_{2,f}$. For a given π_f let $\{\bar\pi_f\}$ be the set of all $\pi_{i,f}$ which are congruent to the given π_f.

$$H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p}))\{\bar\pi_f\} = \{x\in H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p}))|(T_\ell-\bar\pi_f(T_\ell))^N x=0\} \tag{3.73}$$

provided $N >> 0$. Then it is easy to see that (See for instance [book,II], 7.2) that

$$H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p})) = \bigoplus_{\bar\pi_f} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p}))\{\bar\pi_f\} \tag{3.74}$$

The kernel $\mathfrak{m}_{\bar\pi_f}$ of $\bar\pi_f$ is a maximal ideal, let $\mathcal{H}_{\mathfrak{m}_{\bar\pi_f}}$ be the local ring at $\mathfrak{m}_{\bar\pi_f}$. Then the above decomposition can be written as

$$H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p})) = \bigoplus_{\bar\pi_f} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p}))\otimes\mathcal{H}_{\mathfrak{m}_{\bar\pi_f}}/\mathfrak{m}^N_{\bar\pi_f} \tag{3.75}$$

Now we recall that we still have the action of complex conjugation (See sect.2.1.3) on the cohomology and it is clear (SEE(??)) that it commutes with the action of the Hecke algebra. Hence we see that the summands in the above decompose into a + and a - summand, i.e.

$$H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p}))\otimes\mathcal{H}_{\mathfrak{m}_{\bar\pi_f}}/\mathfrak{m}^N_{\bar\pi_f} = \bigoplus_{\pm} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p}))\otimes\mathcal{H}_{\mathfrak{m}_{\bar\pi_f}}/\mathfrak{m}^N_{\bar\pi_f}[\pm] \tag{3.76}$$

Now we encounter some difficult questions. The first one asks whether we have some kind of multiplicity one theorem $\mod \mathfrak{p}$. This question can be formulated as follows:

Are the summands $H^1_{ord}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathbb{F}(\mathfrak{p}))\otimes\mathcal{H}_{\mathfrak{m}_{\bar\pi_f}}/\mathfrak{m}^N_{\bar\pi_f}[\pm]$ cyclic, i.e. are they - as $\mathcal{H}_{\mathfrak{m}_{\bar\pi_f}}/\mathfrak{m}^N_{\bar\pi_f}$ modules - generated by one element ?

To formulate the second question we regroup the decomposition (3.70)

$$H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes F) = \bigoplus_{\bar\pi_f}\Big(\bigoplus_{\pi_f\in\{\bar\pi_f\}} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes F)[\pi_f]\Big) \tag{3.77}$$

$\boxed{\text{pibar}}$ and define

$$\begin{gathered}H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_{\mathfrak{p}})\{\bar\pi_f\} = \\ \Big(\bigoplus\nolimits_{\pi_f\in\{\bar\pi_f\}} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes F)[\pi_f]\Big)\cap H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_{\mathfrak{p}})\end{gathered} \tag{3.78}$$

and then we get a second variant of (3.76)

$$\bigoplus_{\bar\pi_f} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_{\mathfrak{p}})\{\bar\pi_f\} = H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_{\mathfrak{p}}) \tag{3.79}$$

Now we are interested in the structure of the direct summands $H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})\{\bar\pi_f\}$. It is clear that this is a free $\mathcal{O}_\mathfrak{p}$ module of rank

$$r(\{\bar\pi_f\}) = \begin{cases} 2\#\{\bar\pi_f\} & \text{if } \{\bar\pi_f\} \neq \{\bar\pi[^{\mathrm{Eis}}_f\} \\ 2(\#\{\bar\pi_f\}-1)+1 & \text{if } \{\bar\pi_f\} = \{\bar\pi^{\mathrm{Eis}}_f\} \end{cases} \tag{3.80}$$

Again we get a submodule

$$\bigoplus_{\pi_f\in\{\bar\pi_f\}} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})[\pi_f] \subset H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})\{\bar\pi_f\} \tag{3.81}$$

Our second question is

What can we say about the structure of the quotient

$$H^1_{ord}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})\{\bar\pi_f\}/\bigoplus_{\pi_f\in\{\bar\pi_f\}} H^1_{ord}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})[\pi_f]\ ?$$

For instance we may ask: Is this quotient non trivial if the cardinality of $\{\bar\pi_f\}$ is greater than 1 ?

For a subset $\Sigma\subset\{\bar\pi_f\}$ we define in analogy with (3.78)

$$\begin{gathered} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})\{\Sigma\} = \\ (\textstyle\bigoplus_{\pi_f\in\Sigma} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes F)[\pi_f])\cap H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})\{\bar\pi_f\} \end{gathered} \tag{3.82}$$

and we call Σ a block if

$$H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})\{\bar\pi_f\} = \tag{3.83}$$

$$H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})\{\Sigma\}\oplus H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n\otimes\mathcal{O}_\mathfrak{p})\{\{\bar\pi_f\}\setminus\Sigma\} \tag{3.84}$$

Then a slightly stronger version of our question above asks

Can $\{\bar\pi_f\}$ contain non trivial blocks?

These two questions are closely related. We will come back later to these issues in this book. In the following we outline the general philosophy:

The structure of the cohomology as module under the Hecke-algebra is influenced by divisibility of special values of certain L functions which are attached to the π_f.

We have some partial results. (For this see Herbrand -Ribet , Hida..).
If we consider the special case of $\{\bar\pi^{\mathrm{Eis}}_f\}$. Our theorem 3.3.2 implies

$$p\mid\zeta(-1-n)\Rightarrow\{\bar\pi^{\mathrm{Eis}}_f\}>1,$$

this has been proved by Ribet in [ ], he also proves the converse using a theorem of Herbrand [ ]. Our theorem 3.3.2 is stronger, because it implies higher congruences if $\zeta(-1-n)$ is divisible by a higher power of p. Moreover the existence of congruences do not imply anything about the denominator.

Of course the next question is: If we have $p \mid \zeta(-1-n)$, what is the size of $\{\bar{\pi}_f^{\mathrm{Eis}}\}$ can it be > 2? Let us pick a $\pi_f \in \{\bar{\pi}_f^{\mathrm{Eis}}\}$ which is not π_f^{Eis}. To this π_f we attach the so called symmetric square L-function $L(\pi_f, Sym^2, s)$. (See ...). This L function evaluated at a suitable "critical" point and divided by a carefully chosen period gives us a number

$$\mathcal{L}(\pi_f, Sym^2) \in \mathcal{O}_{F_0}$$

here F_0 is a global field whose completion at $\mathfrak{p}$ is our F above. Now a theorem Hida says (cum grano salis)

$$\#\pi_f^{\mathrm{Eis}} > 2 \iff \mathfrak{p} \mid \mathcal{L}(\pi_f, Sym^2) \tag{3.85}$$

(See later) If we accept these two results then we get

Vand

Theorem 3.3.5. *If $p^{\delta_p(n)} \mid \zeta(-1-n)$ and if $\mathcal{L}(\pi_f, Sym^2) \notin \mathfrak{p}$, then the number r in theorem 3.3.2 is equal to one, i.e. $\{\bar{\pi}_f^{\mathrm{Eis}}\} = \{\pi_f, \pi_f^{\mathrm{Eis}})$ and we have the congruence*

$$\pi_f(T_\ell) \equiv \ell^{n+1} + 1 \mod \mathfrak{p}^{\delta_p(n)} \;\forall\; \textit{primes } \ell$$

Finally we get $\pi_f(T_\ell) \in \mathbb{Z}_p$ for all primes ℓ and hence we may take $\mathcal{O}_{\mathfrak{p}} = \mathbb{Z}_p$.

We can find a basis f_0, f_1, f_3 of $H^1_{ord}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})$ where

a) f_1, f_2 form a basis of $H^1_{!,\ ord}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})$

b)The complex conjugation c acts by $c(f_i) = (-1)^{i+1} f_i$

and

c) the matrix $T_\ell^{\ ord}$ with respect to this basis satisfies

$$T_\ell^{\ ord} \equiv \begin{pmatrix} \ell^{n+1}+1 & 0 & 1 \\ 0 & \ell^{n+1}+1 & 0 \\ 0 & 0 & \ell^{n+1}+1 \end{pmatrix} \mod p^{\delta_p(n)}$$

Proof. Clear ∎

If we drop the assumption $\mathcal{L}(\pi_f, Sym^2) \notin \mathfrak{p}$ then the situation becomes definitely more complicated. In this case we we have $\{\bar{\pi}_f^{\mathrm{Eis}}\} = \{\bar{\pi}_f^{\mathrm{Eis}}, \pi_{1,f}, \dots, \pi_{r,f}\}$ where now $r > 1$. We apply theorem 3.3.2 to this situation where we replace the subscript $_{!,\mathrm{int}}$ by $_{\mathrm{ord}}$. We have the filtration which is analogous to (3.57) but now the last quotient is of rank one and isomorphic to the cohomology of the boundary. We find a basis $f_0, f_1, e_1, f_2, e_2, \dots, f_r, e_r$ adapted to this filtration and where $c(f_i) = -f_i, c(e_i) = e_1$ Then we get a matrix (we consider the case $r = 2$)

$$T_\ell^{\mathrm{ord}} = \begin{pmatrix} \ell^{n+1}+1 & 0 & 1 & 0 & 1 \\ 0 & \pi_{f,1}(T_\ell) & 0 & u & 0 \\ 0 & 0 & \pi_{f,1}(T_\ell) & 0 & v \\ 0 & 0 & 0 & \pi_{f,2}(T_\ell) & 0 \\ 0 & 0 & 0 & 0 & \pi_{f,2}(T_\ell) \end{pmatrix} \tag{3.86}$$

where u, v are units in $\mathbb{Z}_p$ and where the diagonal entries satisfy some congruences $\pi_{\nu,1}(T_\ell) \equiv \ell^{n+1} + 1 \mod \mathfrak{p}^{n_\nu}$ where $n_1 + n_2 = e_{\mathfrak{p}}\delta_p(n)$. We come back to this later.

p-adic-zeta

3.3.9 The p-adic ζ-function

We return to section 3.3.7. We are interested in the case that p is an irregular prime, i.e. $p \mid \zeta(-1-n_0)$. We also assume that also $\mathcal{L}(\pi_f, Sym^2) \notin \mathfrak{p}$. We consider $\zeta(-1-n) = \zeta(-1-n_0-\alpha(p-1))$ as function in the variable $\alpha \in \mathbb{N}$ and we want to find values $n = -1-n_0-\alpha(p-1)$ such that $\zeta(-1-n)$ is divisible by higher powers of p. We know that that there exist a p-adic $\zeta-$ function and tells us - provided $n_0 > 0-$ that

$\boxed{\text{p-appr}}$

$$\zeta(-1-n) = \zeta(-1-n_0-\alpha(p-1)) \equiv \zeta(-1-n_0) + a(n_0,1)\alpha p + a(n_0,2)\alpha^2 p^2 \dots \tag{3.87}$$

where the coefficients $a(n_0,\nu) \in \mathbb{Z}_p$. Now several things can happen.

A) Our prime p does not divide the second coefficient $a(n_0,2)$. Then we can apply Newton's method and we find a converging sequence $\alpha_1, \alpha_2, \dots$ such that

$$\alpha_\nu \equiv \alpha_{\nu+1} \mod p^\nu \text{ and } \zeta(-1-n_0-\alpha_\nu(p-1)) \equiv 0 \mod p^{\nu+1} \tag{3.88}$$

If now $n_\nu = n_0 + \alpha_\nu(p-1)$ then we can form the system of Hecke-modules (A Hida family) $H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \mathcal{M}_{n_\nu})(\{\bar{\pi}_f^{\text{Eis}}\})$ and theorem 3.3.4 gives us Hecke-module morphisms

$$H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n_\nu+1} \otimes \mathbb{Z}/p^{\nu+1}\mathbb{Z}) \xrightarrow{\Phi_\nu} H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n_\nu} \otimes \mathbb{Z}/p^\nu\mathbb{Z}) \tag{3.89}$$

The sequence n_ν converges to an p-adic integer n_∞, we can form the projective limit and define

$$H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n_\infty}) = \lim_{\leftarrow} H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n_\nu} \otimes \mathbb{Z}/p^\nu\mathbb{Z}) \tag{3.90}$$

Under our assumptions this is a free $\mathbb{Z}_p$-module of rank 3. The Hecke operators T_ℓ^{ord} acts on $H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n_\nu} \otimes \mathbb{Z}/p^\nu\mathbb{Z})$ by a matrix of the shape as in theorem 3.3.5, and the eigenvalues on the diagonal are

$$\ell^{n_\nu+1} + 1 = \ell^{n_0+(p-1)\alpha_\nu} + 1 \mod p^\nu$$

For $\ell \neq p$ we write $\ell^{p-1} = 1 + \delta(\ell)p, \delta(\ell) \in \mathbb{N}$ and then $\ell^{n_0+(p-1)\alpha_\nu} = \ell^{n_0}(1+\delta(\ell)p)^{\alpha_\nu}$ and hence it follows that $\lim_{\nu\to\infty} \ell^{n_\nu} = \ell^{n_\infty}$ exists. Hence we see that T_ℓ^{ord} acts on $H^1_{\text{ord}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{n_\infty})$ by the matrix

$$T_\ell^{\text{ord}} \equiv \begin{pmatrix} \ell^{n_\infty+1}+1 & 0 & 1 \\ 0 & \ell^{n_\infty+1}+1 & 0 \\ 0 & 0 & \ell^{n_\infty+1}+1 \end{pmatrix}$$

B) We have $p \mid \zeta(-1-n_0); p^2 \not| \zeta(-1-n_0)$ and $p \mid a(n_0,1)$. In this case we can not increase the p power dividing $\zeta(-1-n)$

C) We have $p^2 \mid \zeta(-1-n_0);\ p \mid a(n_0,1)$ and $p \not| a(n_0,2)$
We rewrite (3.87)

$$\frac{\zeta(-1-n)}{p^2} \equiv \frac{\zeta(-1-n_0)}{p^2} + \frac{a(n_0,1)}{p}\alpha + a(n_0,2)\alpha^2 \mod p \tag{3.91}$$

Now we get two numbers $\alpha_\infty, \beta_\infty$ such that

$$\zeta(-1-n_0-\alpha_\infty(p-1)) = 0\,; \zeta(-1-n_0-\beta_\infty(p-1)) = 0$$

but these numbers are not necessarily in $\mathbb{Z}_p$, they lie in a quadratic extension $\mathcal{O}_\mathfrak{p}$ of $\mathbb{Z}_p$ hence they are not necessarily approximable by (positive) integers. If we want to interpret these zeros in terms of cohomology modules with an action of the Hecke algebra we have to extend the range of coefficient systems. In [Ha-Int] we define "coefficient systems" $\mathcal{M}^\dagger_{n_0,\alpha}$ where now is any element in $\mathcal{O}_{\mathbb{C}_p}$. (These coefficient systems are denoted $\mathcal{P}_\chi$ in [Ha-Int]).

These coefficient systems are infinite dimensional $\mathcal{O}_{\mathbb{C}_p}-$ modules, we can define the ordinary cohomology $H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \mathcal{M}^\dagger_{n_0,\alpha})$. On these (ordinary) cohomology modules we have an action of the Hecke algebra and they satisfy the same interpolation properties as the previous ones, especially we have an extension of theorem 3.3.4 for these cohomology modules.

If $\alpha = a$ is a positive integer then we have a natural homomorphism

$$\Psi_a : \mathcal{M}_{n_0+a(p-1)} \to \mathcal{M}^\dagger_{n_0,\alpha}$$

and this map induces an isomorphism on the ordinary part of the cohomology

$\boxed{\text{isop}}$

$$\Psi^{(1)} : H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \mathcal{M}_{n_0+a(p-1)}) \xrightarrow{\sim} H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \mathcal{M}^\dagger_{n_0,\alpha}) \tag{3.92}$$

We now allow any $\alpha \in \mathcal{O}_\mathfrak{p}$, our coefficient system will then be a system of $\mathcal{O}_\mathfrak{p}$ modules and the cohomology modules will be $\mathcal{O}_\mathfrak{p}$ modules. Of course we still have our fundamental exact sequence (3.93) of $\mathcal{O}_\mathfrak{p}$ modules.

$$\to H^1_{\mathrm{ord},c}(\Gamma\backslash\mathbb{H}, \mathcal{M}^\dagger_{n_0,\alpha}) \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \mathcal{M}^\dagger_{n_0,\alpha}) \xrightarrow{r} H^1_{\mathrm{ord}}(\partial(\Gamma\backslash\mathbb{H}),\ \mathcal{M}^\dagger_{n_0,\alpha}) = \mathcal{O}_\mathfrak{p} e_{n_0,\alpha} \to 0 \tag{3.93}$$

This is an exact sequence of Hecke-modules and we still have

$$T_\ell^{\mathrm{ord}}(e_n) = (\ell^{n_0}(\ell^{p-1})^\alpha + 1)e_{n_0,\alpha} \tag{3.94}$$

Let $\mathfrak{p} = (\varpi_p)$, we define $\delta_p(\alpha)$ by

$$\varpi_p^{\delta_p(\alpha)} || \zeta(-1-n_0-\alpha(p-1)).$$

In a forthcoming paper with Mahnkopf we will (hopefully) show that we can construct a section

$\boxed{\text{Eissec}}$

$$\mathrm{Eis}_\alpha : \mathcal{O}_{\mathbb{C}_p} e_{n_0,\alpha} \otimes \mathbb{Q}_p \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \mathcal{M}^\dagger_{n_0,\alpha}) \otimes \mathbb{Q}_p \tag{3.95}$$

which is defined by analytic continuation and that $\varpi_p^{\delta_p(\alpha)}$ is the exact denominator of Eis_α.

If this turns out to be true then we can extend the results for ordinary cohomology modules $H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \mathcal{M}_{n_0+(p-1)\alpha}))$ to the extended class of cohomology modules $H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \mathcal{M}^\dagger_{n_0,\alpha})$. Especially if we look at our roots $\alpha_\infty, \beta_\infty$ and assume that they are different then we get a theorem analogous to the theorem 3.3.5 for both of them. If these two roots are the same the situation is not clear to me.

3.3.10 The Wieferich dilemma

We are still assuming that our group $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$. We get a clean statement if we are in case A), i.e.

$$p \mid \zeta(-1-n_0)\ , p\ \not| \, a(n_0,1)\ , \mathfrak{p}\ \not| \, \mathcal{L}(\pi_f, Sym^2)$$

At the present moment we do not know of any prime $p | \, \zeta(-1-n_0)$ which does not satisfy A). This is is not surprising: The primes $p \mid \zeta(-1-n_0)$ are called the irregular primes and they start with

$$37 \mid \zeta(-1-30), 59 \mid \zeta(-1-42)\dots$$

It is believable that for a prime $p \mid \zeta(-1-n_0)$ the numbers $a(n_0,1)$ and $\mathcal{L}(\pi_f, Sym^2)$ are "unrelated" and or in other words the residue classes $a(n_0,1) \mod p$ and $\mathcal{L}(\pi_f, Sym^2) \mod \mathfrak{p}$ are randomly distributed. Hence we expect that the primes $p \mid \zeta(-1-n_0)$ which do not satisfy A) is a "sparsely distributed".

But this does not say that this never happens, actually depending on the probabilistic argument you prefer, it should happen eventually. But perhaps we will never find such a prime.

On the other hand

The Wieferich dilemma: We do not know whether for all primes $p > T_0 >> 0$ *the assertion A) is wrong.*

We drop our assumption that $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$ and replace it by a normal congruence subgroup of finite index. We choose a free $\mathbb{Z}-$ module of finite rank $\mathcal{V}$ with an action of Γ_0/Γ, i.e. we have a representation

$$\rho_{\mathcal{V}} : \Gamma_0/\Gamma \to \mathrm{Gl}(\mathcal{V})$$

we assume that the matrix $-\mathrm{Id}$ acts by a scalar $\omega_{\mathcal{V}}(-\mathrm{Id}) = \pm 1$. We look at the Γ-modules $\mathcal{M}_n \otimes \mathcal{V}$, we assume that $\mathcal{V}(-\mathrm{Id}) \equiv n \mod 2$, These modules provide sheaves $\widetilde{\mathcal{M}_n \otimes \mathcal{V}}$ and we can study the cohomology groups and especially we can study the fundamental exact sequence

$$\to H^1_{\mathrm{ord},c}(\Gamma\backslash\mathbb{H}, \widetilde{\mathcal{M}_n \otimes \mathcal{V}}) \to H^1_{\mathrm{ord}}(\Gamma\backslash\mathbb{H}, \widetilde{\mathcal{M}_n \otimes \mathcal{V}}) \xrightarrow{r} H^1_{\mathrm{ord}}(\partial(\Gamma\backslash\mathbb{H}), \widetilde{\mathcal{M}_n \otimes \mathcal{V}}) \tag{3.96}$$

We have to compute $H^1_{\mathrm{ord}}(\partial(\Gamma\backslash\mathbb{H}), \widetilde{\mathcal{M}_n \otimes \mathcal{V}})$ as a module under the Hecke algebra and we can ask the denominator question again, provided this boundary cohomology is not trivial.

We may for instance choose a positive integer N and we consider the congruence subgroup $\Gamma_0(N) = \{\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{Sl}_2(\mathbb{Z}) | c \equiv 0 \mod N\}$. Let $\Gamma_1(N) \subset \Gamma_0(N)$ be the subgroup where $a \equiv d \equiv 1 \mod N$ then $\Gamma_0(N)/\Gamma_1(N) = (\mathbb{Z}/N\mathbb{Z})^*$ We choose a character $\chi : \Gamma_0(N)/\Gamma_1(N) \to \mathbb{C}^\times$ and consider the representation $\mathcal{V} = \mathrm{Ind}_{\Gamma_0(N)}^{\Gamma}\chi$. In this case the denominator is essentially given by L values $L(\chi, -1-n)$ and these values will be divisible by smaller primes (compared to 37) and our chances to encounter cases of B) and or C) are much better.

Chapter 4

Representation Theory, Eichler Shimura

HC

4.1 Harish-Chandra modules with cohomology

In Chap.III , section 4 we will give a general discussion of the tools from representation theory and analysis which help us to understand the cohomology of arithmetic groups. Especially in Chap.III 4.1.4 we will recall the results of Vogan-Zuckerman on the cohomology of Harish-Chandra modules.

Here we specialize these results to the specific cases $G = \mathrm{Gl}_2(\mathbb{R})$ (case A)) and $G = \mathrm{Gl}_2(\mathbb{C})$ (case B)). For the general definition of Harish-Chandra modules and for the definition of $(\mathfrak{g}, K_\infty)$ cohomology we refer to Chap.III, 4.

Mlambda

The finite rank highest weight modules

We consider the case A), in this case our group $G/\mathbb{R}$ is the base extension of the the reductive group scheme $\mathcal{G} = \mathrm{Gl}_2/\ \mathrm{Spec}(\mathbb{Z})$. (See Chap. IV for the notion of reductive group scheme.) In principle this a pretentious language. At this point it simply means that we can speak of $\mathcal{G}(R)$ for any commutative ring R with identity and that $\mathcal{G}(R)$ depends functorially on R.(Sometimes in the following we will replace $\mathrm{Spec}(\mathbb{Z})$ by $\mathbb{Z}$) We have the maximal torus $\mathcal{T}/\mathbb{Z}$ and the Borel subgroup $\mathcal{B}/\mathbb{Z}$. We consider the character module $X^*(\mathcal{T}) = X^*(T \times \mathbb{C})$. This character module is $\mathbb{Z}e_1 \oplus \mathbb{Z}e_2$ where

$$e_i : \begin{pmatrix} t_1 & 0 \\ 0 & t_2 \end{pmatrix} \mapsto t_i \tag{4.1}$$

Any character can be written as $\lambda = n\gamma + d\det$ where $\gamma = \frac{e_1 - e_2}{2} (\notin X^*(\mathcal{T})\ !), \det = e_1 + e_2$ and where $n \in \mathbb{Z}, d \in \frac{1}{2}\mathbb{Z}$ and where $n \equiv 2d \mod 2$. (We drop the assumption that n should be even.) To any such character λ we want to attach a highest weight module $\mathcal{M}_\lambda$. We assume that λ is dominant, i.e. $n \geq 0$ and consider the $\mathbb{Z}-$ module of polynomials

$$\mathcal{M}_n = \{P(X,Y) \mid P(X,Y) = \sum_{\nu=0}^{n} a_v X^\nu Y^{n-\nu}, a_\nu \in \mathbb{Z}\}.$$

To a polynomial $P \in \mathcal{M}_n$ we attach the regular function (See Chap. IV)

$$f_P(\begin{pmatrix} x & y \\ u & v \end{pmatrix}) = P(u,v) \det(\begin{pmatrix} x & y \\ u & v \end{pmatrix})^{\frac{n}{2}+d_1} \tag{4.2}$$

and we obviously have

$$f_P(\begin{pmatrix} t_1 & w \\ 0 & t_2 \end{pmatrix}\begin{pmatrix} x & y \\ u & v \end{pmatrix}) = t_2^n (t_1 t_2)^d f_P(\begin{pmatrix} x & y \\ u & v \end{pmatrix}) = \lambda^-(\begin{pmatrix} t_1 & w \\ 0 & t_2 \end{pmatrix}) f_P(\begin{pmatrix} x & y \\ u & v \end{pmatrix}) \tag{4.3}$$

where $\lambda^- = -n\gamma + (\frac{n}{2} + d_1)\det = -n\gamma + d\det$ considered as a character on $\mathcal{B}$. On this module the group scheme $\mathcal{G}/\mathbb{Z}$ acts by right translations:

$$\rho_\lambda(\begin{pmatrix} a & b \\ c & d \end{pmatrix})(f_P)(\begin{pmatrix} x & y \\ u & v \end{pmatrix})) = f_P(\begin{pmatrix} x & y \\ u & v \end{pmatrix}\begin{pmatrix} a & b \\ c & d \end{pmatrix})$$

This is a module for the group scheme $\mathcal{G}/\mathbb{Z}$ it is called the highest weight module for λ and is denoted by $\mathcal{M}_\lambda$. Comment: When we say that $\mathcal{M}_\lambda$ is a module for the group scheme $\mathcal{G}/\mathbb{Z}$ we mean nothing more than that for any commutative ring R with identity we have an action of $\mathcal{G}(R)$ on $\mathcal{M}_n \otimes R$, which is given by (4.2) and depends functorially on R. We can "evaluate" at $R = \mathbb{Z}$ and get the $\Gamma = \mathrm{Gl}_2(\mathbb{Z})$ module $\mathcal{M}_{\lambda,\mathbb{Z}}$. (Actually we should not so much distinguish between the $\mathrm{Gl}_2(\mathbb{Z})$ module $\mathcal{M}_{\lambda,\mathbb{Z}}$ and $\mathcal{M}_\lambda$)

Remark: There is a slightly more sophisticated interpretation of this module. We can form the flag manifold $\mathcal{B}\backslash\mathcal{G} = \mathbb{P}^1/\mathbb{Z}$ and the character λ yields a line bundle $\mathcal{L}_{\lambda^-}$. The group scheme $\mathcal{G}$ is acting on the pair $(\mathcal{B}\backslash\mathcal{G}, \mathcal{L}_{\lambda^-})$ and hence on $H^0(\mathcal{B}\backslash\mathcal{G}, \mathcal{L}_{\lambda^-})$ which is tautologically equal to $\mathcal{M}_\lambda$ (Borel-Weil theorem).

We can do essentially the same in the case B) . In this case we start from an imaginary quadratic extension $F/\mathbb{Q}$ and let $\mathcal{O} = \mathcal{O}_F \subset F$ its ring of integers. We form the group scheme $\mathcal{G}/\mathbb{Z} = R_{\mathcal{O}/\mathbb{Z}}(\mathcal{G}/\mathcal{O})$. Then $\mathcal{G}(\mathcal{O}) = \mathrm{Gl}_2(\mathcal{O} \otimes \mathcal{O}) \subset \mathrm{Gl}_2(\mathcal{O}) \times \mathrm{Gl}_2(\mathcal{O})$. The base change of the maximal torus $T/\mathbb{Q} \subset \mathcal{G} \times_\mathbb{Z} \mathbb{Q}$ is the product $T_1 \times T_2/F$ where the two factors are the standard maximal tori in the two factors Gl_2/F.

We get for the character module

$$X^*(T \times F) = X^*(T_1) \oplus X^*(T_2) = \{n_1\gamma_1 + d_1 \det\} \oplus \{n_2\gamma_2 + d_2 \bar{\det}\} \tag{4.4}$$

where we have to observe the parity conditions $n_1 \equiv 2d_1 \mod 2, n_2 \equiv 2d_2 \mod 2$ Then the same procedure as in case a) provides a free $\mathcal{O}$- module $\mathcal{M}_\lambda$ with an action of $\mathcal{G}(\mathbb{Z})$ on it. To see this action we embed the group $\mathcal{G}(\mathbb{Z}) = \mathrm{Gl}_2(\mathcal{O})$ into $\mathrm{Gl}_2(\mathcal{O}) \times \mathrm{Gl}_2(\mathcal{O})$ by the map $g \mapsto (g, \bar{g})$ where $\bar{g}$ is of course the conjugate. If now our $\lambda = n_1\gamma_1 + d_1 \det_1 + n_2\gamma_2 + d_2 \det_2 = \lambda_1 + \lambda_2$ then we have our two $\mathrm{Gl}_2(\mathcal{O})$ modules $\mathcal{M}_{\lambda_1,\mathcal{O}}, \mathcal{M}_{\lambda_2,\mathcal{O}}$ and hence the $\mathrm{Gl}_2(\mathcal{O}) \times \mathrm{Gl}_2(\mathcal{O})$- module

$\mathcal{M}_{\lambda_1,\mathcal{O}} \otimes \mathcal{M}_{\lambda_2,\mathcal{O}}$, is now our $\mathcal{M}_{\lambda,\mathcal{O}}$ is simply the restriction of this tensor product module to $\mathcal{G}(\mathbb{Z})$.

Sometimes we will also write our character as the sum of the semi simple component and the central component, i.e. $\lambda = \lambda^{(1)} + \delta = (n_1\gamma_1 + n_2\gamma_2) + (d_1 \det_1 + d_2 \det_2)$. The relevant term is the semi simple component, the central component not important at all, it only serves to fulfill the parity condition. If we restrict the representation $\mathcal{M}_\lambda$ to $\mathrm{Sl}_2/\mathbb{Z}$ then the dependence on d disappears. In other words representations with the same semi simple highest weight component only differ by a twist.

Given $\lambda = \lambda^{(1)} + \delta$ we define the dual character as $\lambda^\vee = \lambda^{(1)} - \delta$. For our finite dimensional modules we have

$$\mathcal{M}_\lambda^\vee \otimes \mathbb{Q} \xrightarrow{\sim} \mathcal{M}_{\lambda^\vee} \otimes \mathbb{Q} \tag{4.5}$$

If we consider the modules over the integers the above relation is not true. We define the submodule $\boxed{\text{duallambda}}$

$$\mathcal{M}_n^\vee = \{P(X,Y) \mid P(X,Y) = \sum_{\nu=0}^{n} \binom{n}{\nu} a_\nu X^\nu Y^{n-\nu}, a_\nu \in \mathbb{Z}\}. \tag{4.6}$$

This is a submodule of $\mathcal{M}_n$ and the quotient $\mathcal{M}_n/\mathcal{M}_n^\vee$ is finite. It is also clear that this submodule is invariant under $\mathrm{Sl}_2/\mathbb{Z}$. We introduce some notation

$$e_\nu := X^\nu Y^{n-\nu} \text{ and } e_\nu^\vee := \binom{n}{\nu} X^{n-\nu} Y^\nu, \tag{4.7}$$

the the $e\nu$(resp. $e_\nu^\vee$) for a basis of $\mathcal{M}_n$(resp. $\mathcal{M}_n/\mathcal{M}_n^\vee$).

An easy calculation shows that the pairing $\boxed{\text{pairMn}}$

$$<\,,\,>_\mathcal{M}: (e_\nu, e_\mu^\vee) \mapsto \delta_{\nu,\mu} \tag{4.8}$$

is non degenerate over $\mathbb{Z}$ and invariant under $\mathrm{Sl}_2/\mathbb{Z}$. We can also define the the twisted actions of $\mathcal{G}/\mathbb{Z}$ Of course we can define the twisted modules $\mathcal{M}_\lambda^\vee$ and then we get a $\mathcal{G}/\mathbb{Z}$ invariant non degenerate pairing over $\mathbb{Z}$:

$$<\,,\,>_\mathcal{M}: \mathcal{M}_{\lambda^\vee}^\vee \times \mathcal{M}_\lambda \to \mathbb{Z}$$

In other words

$$(\mathcal{M}_\lambda)^\vee = \mathcal{M}_{\lambda^\vee}^\vee$$

We always consider $\mathcal{M}_\lambda^\vee$ as the above submodule of $\mathcal{M}_\lambda$.

$\boxed{\text{prinseries}}$

4.1.1 The principal series representations

We consider the two real algebraic groups $G = \mathrm{Gl}_2/\mathbb{R}$ case A) and $G = R_{\mathbb{C}/\mathbb{R}}\mathrm{Gl}_2/\mathbb{C}$ (case B). Let $T/\mathbb{R}$, resp.$B/\mathbb{R}$ be the standard diagonal torus (resp.) Borel subgroup. Let us put $Z/\mathbb{R} = \mathbb{G}_m$ (resp. $R_{\mathbb{C}/\mathbb{R}}\mathbb{G}_m$). We have the determinant $\det : G/\mathbb{R} \to Z/\mathbb{R}$ and moreover $Z/\mathbb{R} = \mathit{center}(G/\mathbb{R})$. If we restrict the determinant to the center then this becomes the map $z \mapsto z^2$. The kernel of the determinant is denoted by $G^{(1)}/R$, of course $G^{(1)} = \mathrm{Sl}_2$, resp. $R_{\mathbb{C}/\mathbb{R}}\mathrm{Sl}_2/\mathbb{C}$. Let us denote by $\mathfrak{g}, \mathfrak{g}^{(1)}, \mathfrak{t}, \mathfrak{b}, \mathfrak{z}$ the corresponding Lie-algebras.

In both cases we fix a maximal compact compact subgroup $K_\infty \subset G^{(1)}(\mathbb{R})$:

$$K_\infty = e(\phi) = \{\begin{pmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{pmatrix} |\phi \in \mathbb{R}\} \text{ and } K_\infty = \{\begin{pmatrix} \alpha & \beta \\ -\bar{\beta} & \bar{\alpha} \end{pmatrix} |\alpha\bar{\alpha} + \beta\bar{\beta} = 1\} \tag{4.9}$$

We define extensions $\tilde{K}_\infty = Z(\mathbb{R})^{(0)}K_\infty$, where of course $Z(\mathbb{R})^{(0)}$ is the connected component of the identity. Actually we will consider K_∞ and $\tilde{K}_\infty$ as the groups of real points of a group which is defined over $\mathbb{Q}$. Hence the Lie-algebras $\mathfrak{k}$ and $\tilde{\mathfrak{k}}$ will be $\mathbb{Q}$ -vector spaces.

Our aim is to to construct certain irreducible (differenttiable) representations of $G(\mathbb{R})$ together with their "algebraic skeleton" the associated Harish-Chandra modules. Of course any homomorphism $\eta : Z \to \mathbb{C}^\times$ yields via composition with the determinant a one dimensional $G(\mathbb{R})$ module $\mathbb{C}\eta$. We want to construct infinite dimensional $G(\mathbb{R})$ modules.

We start from a continuous homomorphism (a character) $\chi : T(\mathbb{R}) \to \mathbb{C}^\times$, of course this can also be seen as a character $\chi : B(\mathbb{R}) \to \mathbb{C}^\times$. This allows us to define the induced module

$$I_B^G\chi := \{f : G(\mathbb{R}) \to \mathbb{C} \mid f \in \mathcal{C}_\infty(G(\mathbb{R})), f(bg) = \chi(b)f(g), \ \forall\, b \in B(\mathbb{R}), g \in G(\mathbb{R})\} \tag{4.10}$$

where we require that f should be $\mathcal{C}_\infty$. Then this space of functions is a $G(\mathbb{R})$ - module, the group $G(\mathbb{R})$ acts by right translations: For $f \in I_B^G\chi, g \in G(\mathbb{R})$ we put

$$R_g(f)(x) = f(xg)$$

We know that $G(\mathbb{R}) = B(\mathbb{R}) \cdot \tilde{K}_\infty$. This implies that a function $f \in I_B^G\chi$ is determined by its restriction to K_∞. In other words we have an identification of vector spaces

$$I_B^G\chi = \{f : \tilde{K}_\infty \to \mathbb{C} \mid f(t_ck) = \chi(t_c)f(k), t_c \in \tilde{K}_\infty \cap B(\mathbb{R}), k \in \tilde{K}_\infty\}. \tag{4.11}$$

We put $T_c = B(\mathbb{R}) \cap \tilde{K}_\infty$ and define χ_c to be the restriction of χ to T_c. Then the module on the right in the above equation can be written as $I_{T_c}^{\tilde{K}_\infty}\chi_c$. By its very definition $I_{T_c}^{\tilde{K}_\infty}\chi_c$. is only a K_∞ module.

Inside $I_{T_c}^{\tilde{K}_\infty}\chi_c$ we have the submodule of vectors of finite type

$${}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c := \{f \in I_{T_c}^{\tilde{K}_\infty}\chi_c \mid \text{ the translates } R_k(f) \text{ lie in a finite dimensional subspace}\} \tag{4.12}$$

The famous Peter-Weyl theorem tells us that all irreducible representations (satisfying some continuity condition) are finite dimensional and occur with finite multiplicity in $I_{T_c}^{\tilde{K}_\infty}\chi_c$ and therefore we get

$${}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c = \bigoplus_{\vartheta \in \hat{K}_\infty} V_\vartheta^{m(\vartheta)} = \bigoplus_{\vartheta \in \hat{K}_\infty} {}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c[\vartheta] \tag{4.13}$$

where $\hat{K}_\infty$ is the set of isomorphism classes of irreducible representations of K_∞, where V_ϑ is an irreducible module of type ϑ and where $m(\vartheta)$ is the multiplicity of ϑ in ${}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c$. Of course ${}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c$ is a submodule $I_B^G\chi$, but this submodule is not invariant invariant under the operation of $G(\mathbb{R})$, in other words if $0 \neq f \in {}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c$ and $g \in G(\mathbb{R})$ a sufficiently general element then $R_g(f) \notin {}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c$.

We can differentiate the action of $G(\mathbb{R})$ on $I_B^G\lambda_{\mathbb{R}}$. We have the well known exponential map $\exp : \mathfrak{g} = \mathrm{Lie}(G/\mathbb{R}) \to G(\mathbb{R})$ and we define for $f \in I_B^G, X \in \mathfrak{g}$

$$Xf(g) = \lim_{t\to 0} \frac{f(g\exp(tX)) - f(g)}{t} \tag{4.14}$$

and it is well known and also easy to see, that this gives an action of the Lie-algebra on I_B^G, we have $X_1(X_2f) - X_2(X_1f) = [X_1, X_2]f$. The Lie-algebra is a K_∞ module under the adjoint action and is obvious that for $f \in {}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c[\vartheta]$ the element Xf lies in $\bigoplus_{\vartheta\in\hat{K}_\infty} {}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c[\vartheta']$ where ϑ' runs over the finitely many isomorphism types occurring in $V_\vartheta \otimes \mathfrak{g}$.

Proposition 4.1.1. *The submodule ${}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c \subset I_B^G\chi$ is invariant under the action of $\mathfrak{g}$.*

The submodule ${}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c$ together with this action of $\mathfrak{g}$ will now be denoted by $\mathfrak{I}_B^G\chi$. Such a module will be called a $(\mathfrak{g}, K_\infty)$ - module or a Harish-Chandra module this means that we have an action of the Lie-algebra $\mathfrak{g}$, an action of K_∞ and these two actions satisfy some obvious compatibility conditions.

We also observe that ${}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c$ is also invariant under right translation R_z for $z \in Z(\mathbb{R})$. Hence we can extend the action of K_∞ to the larger group $\tilde{K}_\infty = K_\infty \cdot Z(\mathbb{R})$. Then $\mathfrak{I}_B^G\chi$ becomes a $(\mathfrak{g}, \tilde{K}_\infty)$ module. Finally observe that in the case A) the element $\mathbf{c} = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \notin \tilde{K}_\infty$, but obviously for $f \in \mathfrak{I}_B^G\chi$ the element $R_{\mathbf{c}}(f) \in \mathfrak{I}_B^G\chi$, hence $R_{\mathbf{c}}$ induces an involution on $\mathfrak{I}_B^G$. We could also say that we can enlarge K_∞(resp. $\tilde{K}_\infty$) to subgroups $K_\infty^*(resp. \tilde{K}_\infty^*)$ which contain $\mathbf{c}$ and contain K_∞ resp. $\tilde{K}_\infty$ as subgroups of index two. Then $\mathfrak{I}_B^G\chi$ also becomes a $(\mathfrak{g}, \tilde{K}_\infty^*)$ module.

These $(\mathfrak{g}, \tilde{K}_\infty)$ modules $\mathfrak{I}_B^G\chi$ are called the principal series modules.

We denote the restriction of χ to the central torus $Z = \{\begin{pmatrix} t & 0 \\ 0 & t \end{pmatrix}\}$ by ω_χ. Then $Z(\mathbb{R})$ acts on $\mathfrak{I}_B^G\chi$ by the *central character* character ω_χ, i.e. $R_z(f) = \omega_\chi(z)f$. Once we fix the central character, then there is no difference between $(\mathfrak{g}, \tilde{K}_\infty)$ and $(\mathfrak{g}, K_\infty)$ modules.

The decomposition into K_∞-types

$\boxed{\text{Kutypes}}$

We look briefly at the K_∞-module ${}^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c$. In case A) the group

$$K_\infty = SO(2) = \{\begin{pmatrix} \cos(\phi) & \sin(\phi) \\ -\sin(\phi) & \cos(\phi) \end{pmatrix} = e(\phi)\} \tag{4.15}$$

and $T_c = T(\mathbb{R}) \cap K_\infty$ is cyclic of order two with generator $e(\pi)$. Then χ_c is given by an integer $\mod 2$, i.e. $\chi_c(e(\pi)) = (-1)^m$. For any $n \equiv m \mod 2$ we define $\psi_n \in \mathfrak{I}_B^G\chi$ by

$$\psi_n(e(\phi))) = e^{in\phi} \tag{4.16}$$

and then $\boxed{\text{decoKuA}}$

$$\mathfrak{I}_B^G\chi = \bigoplus_{k\equiv m \mod 2} \mathbb{C}\psi_k \tag{4.17}$$

In the case B) the maximal compact subgroup is

$$U(2) \subset G(\mathbb{R}) = R_{\mathbb{C}/\mathbb{R}}(\mathrm{Gl}_2/\mathbb{C})(\mathbb{R}) \subset \mathrm{Gl}_2(\mathbb{C}) \times \mathbb{G}_2(\mathbb{C})$$

this is the group of real points of the reductive group $U(2)/\mathbb{R}$. The intersection

$$T_c = T(\mathbb{R}) \cap K_\infty = \{\begin{pmatrix} e^{i\phi_1} & 0 \\ 0 & e^{i\phi_2} \end{pmatrix} = e(\underline{\phi})\}.$$

The base change $U(2) \times \mathbb{C} = \mathrm{Gl}_2/\mathbb{C}$ and $T_c \times \mathbb{C}$ becomes the standard maximal compact torus. The irreducible finite dimensional $U(2)$-modules are labelled by dominant highest weights $\lambda_c = n\gamma_c + d\det \in X^*(T_c \times \mathbb{C})$ (See section (4.1), here again $n \geq 0, n \in \mathbb{Z}, n \equiv 2d \mod 2$ and $\gamma_c(e(\underline{\phi})) = e^{i(\phi_1-\phi_2)/2}$.)

We denote these modules by $\mathcal{M}_{\lambda_c}$ after base change to $\mathbb{C}$ they become the modules $\mathcal{M}_{\lambda,\mathbb{C}}$.

As a subgroup of $G(\mathbb{R}) \subset \mathrm{Gl}_2(\mathbb{C}) \times \mathbb{G}_2(\mathbb{C})$ our torus is

$$T_c = \{\begin{pmatrix} e^{i\phi_1} & 0 \\ 0 & e^{i\phi_2} \end{pmatrix} \times \begin{pmatrix} e^{-i\phi_1} & 0 \\ 0 & e^{-i\phi_2} \end{pmatrix}\} \xrightarrow{\sim} \{\begin{pmatrix} e^{i\phi_1} & 0 \\ 0 & e^{i\phi_2} \end{pmatrix}\} \tag{4.18}$$

and the restriction of χ to T_c is of the form

$$\chi_c(e(\underline{\phi})) = e^{ia\phi_1+ib\phi_2} = e^{\frac{a-b}{2}(\phi_1-\phi_2)}e^{\frac{a+b}{2}(\phi_1+\phi_2)} \tag{4.19}$$

and this character is $(a-b)\gamma_c + \frac{a+b}{2}\det$. Then we know

$\boxed{\text{decoKuB}}$

$$^\circ I_{T_c}^{\tilde{K}_\infty}\chi_c = \mathfrak{I}_B^G\chi = \bigoplus_{\mu_c=k\gamma_c+\frac{a+b}{2}\det; k\equiv(a-b) \mod 2; k\geq|a-b|} \mathcal{M}_{\mu_c} \tag{4.20}$$

$\boxed{\text{IndInt}}$

The $\mathcal{O}_f$ structure on the modules $\mathfrak{I}_B^G\chi$

Intertwining operators

Let $N(T)$ the normalizer of $T/\mathbb{R}$, the quotient $W = N(T)/T$ is a finite group scheme. The in our case the group $W(\mathbb{R})$ is cyclic of order 2 and generated by

$$w_0 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

In case a) we have $W(\mathbb{R}) = W(\mathbb{C})$ in case b) we have

$$G \times_{\mathbb{R}} \mathbb{C} = (\mathrm{Gl}_2 \times \mathrm{Gl}_2)/\mathbb{C}\ ;\ T \times_{\mathbb{R}} \mathbb{C} = T_1 \times T_2\ ;\ \text{ and } W(\mathbb{C}) = \mathbb{Z}/2 \times \mathbb{Z}/2$$

where the two factors are generated by $s_1 = (w_0, 1), s_2 = (1, w_0)$. The group $W(\mathbb{R})$ is the group of real points of the Weyl group, the group $W = W(\mathbb{C})$ is the Weyl group or the absolute Weyl group.

We introduces the special character

$$|\rho| : \begin{pmatrix} t_1 & u \\ 0 & t_2 \end{pmatrix} \to |\frac{t_1}{t_2}|^{\frac{1}{2}}$$

The group $W(\mathbb{R})$ acts on $T(\mathbb{R})$ by conjugation and hence it also acts on the group of characters, we denote this action by $\chi \mapsto \chi^w$. We define the twisted action

$$w \cdot \chi = (\chi|\rho|)^w |\rho|^{-1}$$

We recall some well known facts

i) We have a non degenerate $(\mathfrak{g}, K_\infty)$ invariant pairing

$$\mathfrak{I}_B^G \chi \times \mathfrak{I}_B^G \chi^{w_0} |\rho|^2 \to \mathbb{C}\omega_\chi^2 \text{ given by } (f_1, f_2) \mapsto \int_{K_\infty} f_1(k) f_2(k) dk \tag{4.21}$$

We define the dual $\mathfrak{I}_B^{G,\vee}\chi$ of a Harish-Chandra as a submodule of $\mathrm{Hom}_{\mathbb{C}}(\mathfrak{I}_B^G\chi, \mathbb{C})$, it consists of those linear maps which vanish on almost all K_∞ types. It is clear that this is again a $(\mathfrak{g}, K_\infty)$-module. The above assertion can be reformulated

ii) We have an isomorphism of $(\mathfrak{g}, K_\infty)$ modules

$$\mathfrak{I}_B^G \chi \delta_\chi \to \mathfrak{I}_B^{G,\vee} \chi^{w_0} |\rho|^2 \tag{4.22}$$

The group $T(\mathbb{R}) = T_c \times (\mathbb{R}^\times_{>0})^2$ and hence we can write any character χ in the form

$$\chi(t) = \chi_c(t) |t_1|^{z_1} |t_2|^{z_2} \tag{4.23}$$

where $z_1, z_2 \in \mathbb{C}$.

For $f \in \mathfrak{I}_B^G\chi, g \in G(\mathbb{R})$ we consider the integral

$$T_\infty^{\mathrm{loc}}(f)(g) = \int_{U(\mathbb{R})} f(w_0 u g) du \tag{4.24}$$

It is well known and easy to check that these integrals converge absolutely and locally uniformly for $\Re(z_1 - z_2) >> 0$ and it is also not hard to see that they extend to meromorphic functions in the entire $\mathbb{C}^2$. We can "evaluate" them at all (z_1, z_2) by suitably regularizing at poles (for instance taking residues). This needs some explanation. To define the regularized intertwining operator we consider the "deformed" intertwining operator

$$T_\infty^{\mathrm{loc}}(\lambda_{\mathbb{R}}^{w_0}|\gamma|^z) : \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} |\gamma|^z \to \mathfrak{I}_B^G \lambda_{\mathbb{R}} |\rho|^2 |\gamma|^{-z} \tag{4.25}$$

(See 4.24, $\chi = \lambda_{\mathbb{R}}^{w_0}|\gamma|^z$) and this integral converges if $\Re(z) >> 0$. We have decomposed

$$\mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} |\gamma|^z = \bigoplus_{\vartheta \in \hat{K}_\infty} {}^\circ I_{T_c}^{\tilde{K}_\infty} \chi_c[\vartheta] = \bigoplus_{\vartheta \in \hat{K}_\infty} \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} |\gamma|^z [\vartheta]$$

and our intertwining operator is a direct sum of linear maps between finite dimensional vector spaces

$$c(\lambda_{\mathbb{R}}^{w_0}|\gamma|^z, \vartheta) : \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} |\gamma|^z [\vartheta] \to \mathfrak{I}_B^G \lambda_{\mathbb{R}} |\rho|^2 |\gamma|^{-z} [\vartheta]$$

The finite dimensional vector spaces do not depend on z and the $c(\lambda_{\mathbb{R}}^{w_0}|\gamma|^z,\vartheta)$ can be expressed in terms of values of the $\Gamma-$ function. Especially they are meromorphic functions in the variable z (See sl2neu.pdf,). Hence we can can find an integer $m \geq 0$ such that

$$z^m \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0}|\gamma|^z|_{z=0} : \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \to \mathfrak{I}_B^G \lambda_{\mathbb{R}}|\rho|^2$$

is a non zero intertwining operator and this is now our regularized operator $T_\infty^{\mathrm{loc,reg}}(\lambda_{\mathbb{R}}^{w_0})$.

iii) The regularized values define non zero intertwining operators

$$T_\infty^{\mathrm{loc,reg}}(\chi) : \mathfrak{I}_B^G \chi \to \mathfrak{I}_B^G \chi^{w_0}|\rho|^2 \tag{4.26}$$

These operators span the one dimensional space of intertwining operators

$$\mathrm{Hom}_{(\mathfrak{g},K_\infty)}(\mathfrak{I}_B^G \chi, \mathfrak{I}_B^G w_0 \cdot \chi).$$

Finally we discuss the question which of these representations are unitary. This means that we have to find a pairing

$$\psi : \mathfrak{I}_B^G \chi \times \mathfrak{I}_B^G \chi \to \mathbb{C} \tag{4.27}$$

which satisfies

a) it is linear in the first and conjugate linear in the second variable

b) It is positive definite, i.e. $\psi(f,f) > 0 \; \forall f \in \mathfrak{I}_B^G \chi$

c) It is invariant under the action of K_∞ and Lie-algebra invariant under the action of $\mathfrak{g}$, i.e. we have

For $f_1, f_2 \in \mathfrak{I}_B^G \chi$ and $X \in \mathfrak{g}$ we have $\psi(Xf_1, f_2) + \psi(f_1, Xf_2) = 0$.

We are also interested in quasi-unitatry modules. This is notion is perhaps best explained if and instead of c) we require

d) There exists a continuous homomorphism (a character) $\eta : G(\mathbb{R}) \to \mathbb{R}^\times$ such that $\psi(gf_1, gf_2) = \eta(g)\psi(f_1, f_2), \; \forall g \in G(\mathbb{R}), f_1 f_2 \in \mathfrak{I}_B^G \chi$

It is clear that a non zero pairing ψ which satisfies a) and c) is the same thing as a non zero $(\mathfrak{g}, K_\infty)$-module linear map

$$i_\psi : \mathfrak{I}_B^G \chi \to \overline{(\mathfrak{I}_B^G \chi)^\vee} \tag{4.28}$$

by definition i_ψ is a conjugate linear map from $\mathfrak{I}_B^G \chi$ to $(\mathfrak{I}_B^G \chi)^\vee$. The map i_ψ and the pairing ψ are related by the formula $\psi(v_1, v_2) = i_\psi(v_2)(v_1)$.

Of course we know that (See (4.22))

$$\overline{(\mathfrak{I}_B^G \chi)^\vee} \xrightarrow{\sim} \mathfrak{I}_B^G \overline{\chi^{w_0}|\rho|^2 \delta_\chi^{-1}} \tag{4.29}$$

and we find such an i_ψ if

$$\chi = \overline{\chi^{w_0}|\rho|^2 \delta_\chi^{-1}} \text{ or } \chi^{w_0}|\rho|^2 = \overline{\chi^{w_0}|\rho|^2 \delta_\chi^{-1}} \tag{4.30}$$

We write our χ in the form (4.23). A necessary condition for the existence of a hermitian form is of course that all $|\omega_\chi(x)| = 1$ for $x \in Z(\mathbb{R})$ and this means that $\Re(z_1 + z_2) = 0$, hence we write

$$z_1 = \sigma + i\tau_1, z_2 = -\sigma + i\tau_2 \tag{4.31}$$

Then the two conditions in (4.30) simply say

$$(\mathrm{un}_1) : \sigma = \frac{1}{2} \text{ or } (\mathrm{un}_2) : \tau_1 = \tau_2 \text{ and } \chi_c = \chi_c^{w_0} \tag{4.32}$$

In both cases we can write down a pairing which satisfies a) and c). We still have to check b). In the first case, i.e. $\sigma = \frac{1}{2}$ we can take the map $i_\psi = \mathrm{Id}$ and then we get for $f_1, f_2 \in \mathfrak{I}_B^G\chi$ the formula

$$\psi(f_1, f_2) = \int_{K_\infty} f_1(k)\overline{f_2(k)}dk \tag{4.33}$$

and this is clearly positive definite. These are the representation of the unitary principal series.

In the second case we have to use the intertwining operator in (4.26) and write

$$\psi(f_1, f_2) = T_\infty^{\mathrm{loc,reg}}(f_2)(f_1) \tag{4.34}$$

Now it is not clear whether this pairing satisfies b). This will depend on the parameter σ. We can twist by a character $\eta : Z(\mathbb{R}) \to \mathbb{C}^\times$ and achieve that $\chi_c = 1, \tau_1 = \tau_2 = 0$. We know that for $\sigma = \frac{1}{2}$ the intertwining operator T_∞^{loc} is regular at χ and since in addition under these conditions $\mathfrak{I}_B^G\chi$ is irreducible we see that

$$T_\infty^{\mathrm{loc}}(\chi) = \alpha \,\mathrm{Id} \text{ with } \alpha \in \mathbb{R}_{>0}^\times \tag{4.35}$$

Since we now are in case a) and b) at the same time we see that the two pairings defined by the rule in case (un_1) and (un_2) differ by a positive real number hence the pairing defined in (4.34) is positive definite if $\sigma = \frac{1}{2}$.

But now we can vary σ. It is well known that $\mathfrak{I}_B^G\chi$ stays irreducible as long as $0 < \sigma < 1$ (See next section) and since $T_\infty^{\mathrm{loc}}(\chi)(f)(f)$ varies continuously we see that (4.34) defines a positive definite hermitian product on $\mathfrak{I}_B^G\chi$ as long as $0 < \sigma < 1$. This is the supplementary series. What happens if we leave this interval will be discussed in the next section.

$\boxed{\text{nontriv}}$

4.1.2 Reducibility and representations with non trivial cohomology

As usual we denote by $\rho \in X^*(T) \otimes \mathbb{Q}$ the half sum of positive roots we have $\rho = \gamma($ resp. $\rho = \gamma_1 + \gamma_2 \in X^*(T) \otimes \mathbb{Q}$ in case A) (resp. B)).

For any character $\lambda \in X^*(T \times \mathbb{C})$ we define $\lambda_\mathbb{R}$ to be the restriction (or evaluation)

$$\lambda_\mathbb{R} : T(\mathbb{R}) \to \mathbb{C}^\times.$$

This provides a homomorphism $B(\mathbb{R}) \to T(\mathbb{R})$ and hence we get the Harish-Chandra modules $\mathfrak{I}_B^G\lambda_\mathbb{R}$ which are of special interest for our subject namely the cohomology of arithmetic groups.

We just mention the fact that $\mathfrak{I}_B^G\chi$ is always irreducible unless $\chi = \lambda_\mathbb{R}$ (See sl2neu.pdf, Condition (red)).

We return to the situation discussed in section (4.1), especially we reintroduce the field $F/\mathbb{Q}$. Then we have $X^*(T \times F) = X^*(T \times \mathbb{C})$ and hence $\lambda \in X^*(T \times F)$. We assume that λ is dominant, i.e. $n \geq 0$ in case A) or $n_1, n_2 \geq 0$ in case B). In this case we realized our modules $\mathcal{M}_\lambda$ as submodules in the algebra of regular functions on $\mathcal{G}/\mathbb{Z}$ and if we look at the definition (See (4.3)) we see immediately that $\mathcal{M}_{\lambda,\mathbb{C}} \subset \mathfrak{I}_B^G\lambda_\mathbb{R}^{w_0}$ and hence we get an exact sequence of $(\mathfrak{g}, K_\infty)$ modules $\boxed{\text{seq}}$

$$0 \to \mathcal{M}_{\lambda,\mathbb{C}} \to \mathfrak{I}_B^G\lambda_\mathbb{R}^{w_0} \to \mathcal{D}_\lambda \to 0 \tag{4.36}$$

Hence we see that $\mathfrak{I}_B^G\lambda_\mathbb{R}^{w_0}$ is not irreducible. We can also look at the dual sequence. Here we recall that we wrote $\lambda = n\gamma + d\det$. Then we will see later that $\mathcal{M}_{\lambda,\mathbb{C}}^\vee = \mathcal{M}_{\lambda - 2d\det,\mathbb{C}}$. Hence after twisting the dual sequence becomes

$$0 \to \mathcal{D}_\lambda^\vee \otimes \det{}_\mathbb{R}^{2d} \to \mathfrak{I}_B^{G,\vee}\lambda_\mathbb{R}^{w_0} \to \mathcal{M}_{\lambda,\mathbb{C}} \to 0 \tag{4.37}$$

Equation (4.22) yields $\mathfrak{I}_B^{G,\vee}\lambda_\mathbb{R}^{w_0} \xrightarrow{\sim} \mathfrak{I}_B^G\chi|\rho|^2$ and our second sequence becomes

$$0 \to \mathcal{D}_\lambda^\vee \otimes \det{}_\mathbb{R}^{2d} \to \mathfrak{I}_B^G\lambda_\mathbb{R}|\rho|^2 \to \mathcal{M}_{\lambda,\mathbb{C}} \to 0 \tag{4.38}$$

Now we consider the two middle terms in the two exact sequences (4.36,4.38) above. The equation (4.26) claims that we have two non zero *regularized* intertwining operators

$$T_\infty^{\mathrm{loc,reg}}(\lambda_\mathbb{R}^{w_0}) : \mathfrak{I}_B^G\lambda_\mathbb{R}^{w_0} \to \mathfrak{I}_B^G\lambda_\mathbb{R}|\rho|^2 \;\; ; T_\infty^{\mathrm{loc,reg}}(\lambda_\mathbb{R}|\rho|^2) : \mathfrak{I}_B^G\lambda_\mathbb{R}|\rho|^2 \to \mathfrak{I}_B^G\lambda_\mathbb{R}^{w_0} \tag{4.39}$$

If we now look more carefully at our two regularized intertwining operators above then a simple computation yields (see sl2neu.pdf)

Proposition 4.1.2. *The kernel of $T_\infty^{loc,\mathrm{reg}}(\lambda_\mathbb{R}^{w_0})$ is $\mathcal{M}_{\lambda,\mathbb{C}}$ and this operator induces an isomorphism*

$$\bar{T}(\lambda_R) : \mathcal{D}_\lambda \xrightarrow{\sim} \mathcal{D}_\lambda^\vee \otimes \det{}_\mathbb{R}^{2d}$$

(Remember λ is dominant) The kernel of $T_\infty^{loc,\mathrm{reg}}(\lambda_\mathbb{R}|\rho|^2)$ is $\mathcal{D}_\lambda^\vee \otimes \det_\mathbb{R}^{2d}$ and it induces an isomorphism of $\mathcal{M}_{\lambda,\mathbb{C}}$.

The module $\mathfrak{I}_B^G\chi$ is reducible if $T_\infty^{loc,\mathrm{reg}}(\chi)$ not an isomorphism and this happens if an only if $\chi = \lambda_\mathbb{R}$ or $\lambda_\mathbb{R}^{w_0}|\rho|^2$ and λ dominant. (There is one exception to the converse of the above assertion, namely in the case A) and $\sigma = \frac{1}{2}$ and $\chi_c^{w_0} \neq \chi_c$.)

For us of of relevance is to know whether we have a positive definite hermitian form on the $(\mathfrak{g}, K_\infty)$-modules $\mathcal{D}_\lambda$. To discuss this question we treat the cases A) and B) separately.

We look at the decomposition into K_∞-types. (See (4.17)) In case A) (See (4.17)) it is clear that $\mathcal{M}_{\lambda,\mathbb{C}}$ is the direct sum of the K_∞ types $\mathbb{C}\psi_l$ with $|l| \le n$. Hence $\boxed{\text{KTA}}$

$$\mathcal{D}_\lambda = \bigoplus_{k\le -n-2, k\equiv m(2)} \mathbb{C}\psi_k \oplus \bigoplus_{k\ge n+2, k\equiv m(2)} \mathbb{C}\psi_k = \mathcal{D}_\lambda^- \oplus \mathcal{D}_\lambda^+ \tag{4.40}$$

Proposition 4.1.3. *The representations $\mathcal{D}_\lambda^-, \mathcal{D}_\lambda^+$ are irreducible, these are the discrete series representations. The element* $\mathbf{c}$ *interchanges $\mathcal{D}_\lambda^-, \mathcal{D}_\lambda^+$ hence e $\mathcal{D}_\lambda$ is an irreducible $(\mathfrak{g}, \tilde{K}_\infty^*)$ module.*

The operator $\bar{T}(\lambda_R)$ induces a quasi-unitary structure on the $(\mathfrak{g}, \tilde{K}_\infty)$-module $\mathcal{D}_\lambda$. The two sets of K_∞ types occurring in $\mathcal{M}_{\lambda,\mathbb{C}}$ and in $\mathcal{D}_\lambda$ (resp.) are disjoint.

Proof. Remember that as a vector space $\mathcal{D}_\lambda^\vee \otimes \det_{\mathbb{R}}^{2d} = \mathcal{D}_\lambda^\vee$, only the way how $\tilde{K}_\infty$ acts is twisted by $\det_{\mathbb{R}}^{2d}$. Then the form

$$h_\psi(f_1, f_2) = T_\infty^{\text{loc,reg}}(\lambda_{\mathbb{R}}^{w_0})(f_2)(f_1) \tag{4.41}$$

defines a quasi invariant hermitian form. It is positive definite (for more details see sl2neu.pdf). □

A similar argument works in case B).We restrict the $\mathrm{Gl}_2(\mathbb{C}) \times \mathrm{Gl}_2(\mathbb{C})$ module $\mathcal{M}_{\lambda,\mathbb{C}}$ to $U(2) \times U(2)$ then it becomes the highest weight module $\mathcal{M}_{\lambda_c} = \mathcal{M}_{\lambda_{1,c}} \otimes \mathcal{M}_{\lambda_{2,c}}$. (See4.1) Under the action of $U(2) \subset U(2) \times U(2)$ it decomposes into $U(2)$ types according to the Clebsch-Gordan formula $\boxed{\text{CG}}$

$$\mathcal{M}_{\lambda_c}|_{U(2)} = \bigoplus_{\mu_c = k\gamma_c + \frac{d_1+d_2}{2}\det; k\equiv(n_1-n_2) \mod 2; n_1+n_2\ge k\ge |n_1-n_2|} \mathcal{M}_{\mu_c} \tag{4.42}$$

Hence we get $\boxed{\text{KTB}}$

$$\mathcal{D}_{\lambda_c}|_{U(2)} = \bigoplus_{\mu_c = k\gamma_c + \frac{d_1+d_2}{2}\det; k\equiv(n_1-n_2) \mod 2; k\ge n_1+n_2+2} \mathcal{M}_{\mu_c} \tag{4.43}$$

Again we have $\boxed{\text{unitary}}$

Proposition 4.1.4. *The operator $T_\infty^{loc,\text{reg}}(\lambda_{\mathbb{R}}^{w_0})$ induces an isomorphism*

$$\bar{T}(\lambda_R) : \mathcal{D}_\lambda \xrightarrow{\sim} \mathcal{D}_\lambda^\vee \otimes \det{}_{\mathbb{R}}^{2d}$$

The $(\mathfrak{g}, K_\infty)$ modules are irreducible.

The operator $T_\infty^{loc,\text{reg}}(\lambda_{\mathbb{R}}^{w_0})$ induces the structure of a quasi-unitary module on $\mathcal{D}_\lambda$ if and only if $n_1 = n_2$. This is the only case when we have a quasi-unitary structure on $\mathcal{D}_\lambda$. The two sets of K_∞ types occurring in $\mathcal{M}_{\lambda,\mathbb{C}}$ and in $\mathcal{D}_\lambda$ (resp.) are disjoint.

The Weyl W group acts on T by conjugation, hence on $X^*(T \times \mathbb{C})$ and we define the twisted action by

$$s \cdot \lambda = s(\lambda + \rho) - \rho \tag{4.44}$$

Given a dominant λ we may consider the four characters $w \cdot \lambda, w \in W(\mathbb{C}) = W$ and the resulting induced modules $\mathfrak{I}_B^G w \cdot \lambda_{\mathbb{R}}$. We observe (notation from (4.1))

$$\begin{aligned} s_1 \cdot (n_1\gamma + d_1 \det + n_2\bar{\gamma} + d_2\overline{\det}) &= (-n_1 - 2)\gamma + d_1 \det + n_2\bar{\gamma} + d_2\overline{\det}) \\ s_2 \cdot (n_1\gamma + d_1 \det + n_2\bar{\gamma} + d_2\overline{\det}) &= n_1\gamma + d_1 \det + (-n_2 - 2)\bar{\gamma} + d_2\overline{\det}) \end{aligned} \tag{4.45}$$

Looking closely we see that that the K_∞ types occurring in $\mathfrak{I}_B^G s_1 \cdot \lambda$ or $\mathfrak{I}_B^G s_2 \cdot \lambda$ are exactly those which occur in $\mathcal{D}_\lambda$. This has a simple explanation, we have $\boxed{\text{exiso}}$

Proposition 4.1.5. *For a dominant character λ we have isomorphisms between the $(\mathfrak{g}, K_\infty)$ modules*

$$\mathcal{D}_\lambda \xrightarrow{\sim} \mathfrak{I}_B^G s_1 \cdot \lambda, \; \mathcal{D}_\lambda \xrightarrow{\sim} \mathfrak{I}_B^G s_2 \cdot \lambda. \tag{4.46}$$

The resulting isomorphism $\mathfrak{I}_B^G s_1 \cdot \lambda \xrightarrow{\sim} \mathfrak{I}_B^G s_2 \cdot \lambda$ is of course given by $T_\infty^{\mathrm{loc}}(s_1 \cdot \lambda)$.

Interlude: Here we see a fundamental difference between the two cases A) and B). In the second case the infinite dimensional subquotients of the induced representations are again induced representations. In the case A) this is not so, the representations $\mathcal{D}_\lambda^\pm$ are not isomorphic to representations induced from the Borel subgroup.

These representation $\mathcal{D}_\lambda^\pm$ are called discrete series representations and we want to explain briefly why. Let G be the group of real points of a reductive group over $\mathbb{R}$ for example our $G = G(\mathbb{R})$, here we allow both cases. Let Z be the center of G, it can be written as $Z_0(\mathbb{R}) \cdot Z_c$ where Z_c is maximal compact and $Z_0 = (\mathbb{R}_{>0}^\times)^t$. Let $\omega^{(0)} : Z_0 \to \mathbb{R}_{>0}^\times$ be a character. Then we define the space

$$\mathcal{C}_\infty(G, \omega_R) := \{f \in \mathcal{C}(G) \mid f(zg) = \omega^{(0)}(z)f(g) \,; \forall z \in Z_0, g \in G\} \tag{4.47}$$

and we define the subspace

$$L^2_\infty(G, \omega_R) := \{f \in \mathcal{C}_\infty(G, \omega_R) \mid \int_G f(g)\overline{f(g)}(\omega^{(0)}(g))^{-2} dg < \infty\} \tag{4.48}$$

where of course dg is a Haar measure. As usual $L^2(G, \omega_R)$ will be the Hilbert space obtained by completion. This Hilbert space only depends in a very mild way on the choice of $\omega^{(0)}$ we can find a character $\delta : G \to \mathbb{R}_{>0}^\times$ such that $\omega^{(0)}\delta|_{Z_0} = 1$. Then $f \mapsto f\delta$ provides an isomorphism $L^2(G, \omega^{(0)}) \xrightarrow{\sim} L^2(G/Z_0)$.

We have an action of $G \times G$ on $L^2(G, \omega^{(0)}))$ by left and right translations. Then Harish-Chandra has investigated the question how this "decomposes" into irreducible submodules. Let $\hat{G}_{\omega^{(0)})}$ be the set of isomorphism classes of irreducible unitary representations of G.

Then Harish-Chandra shows that there exist a positive measure μ on $\hat{G}_{\omega^{(0)})}$ and a measurable family H_ξ of irreducible unitary representations of G such that

$$L^2(G, \omega_{\mathbb{R}}) = \int_{\hat{G}_{\omega_{\mathbb{R}}}} H_\xi \otimes \overline{H_\xi} \; \mu(d\xi) \tag{4.49}$$

(If instead of a semi simple Lie group we take a finite group G then this is the fundamental theorem of Frobenius that the group ring $\mathbb{C}[G] = \oplus_\theta V_\theta \otimes V_\theta^\vee$ where V_θ are the irreducible representations.)

If we are in the case A) then the sets consisting of just one point $\{\mathcal{D}_\lambda^\pm\}$ have strictly positive measure, i.e. $\mu(\{\mathcal{D}_\lambda^\pm\}) > 0$. This means that the irreducible unitary $G \times G$ modules $\mathcal{D}_\lambda^\pm \otimes \mathcal{D}_{\lambda^\vee}^\pm$ occur as direct summand (i.e. discretely in $L^2(G)$.).

Such irreducible direct summands do not exist in the case B), in this case for any $\xi \in \hat{G}$ we have $\mu(\{\xi\}) = 0$.

We return to the sequences (4.36),(4.38). We claim that both sequences do do not split as sequences of $(\mathfrak{g}, K_\infty)$-modules. Of course it follows from the above proposition that these sequences split canonically as sequence of K_∞ modules. But then it follows easily that complementary summand is not invariant under the action of $\mathfrak{g}$. This means that the sequences provide non trivial classes in $\mathrm{Ext}^1_{(\mathfrak{g},K_\infty)}(\mathcal{D}_\lambda, \mathcal{M}_{\lambda,\mathbb{C}})$ and hence these $\mathrm{Ext}^\bullet$ modules are interesting.

The general principles of homological algebra teach us that we can understand these extension groups in terms of relative Lie-algebra cohomology. Let $\mathfrak{k}$ resp. $\tilde{\mathfrak{k}}$ be the Lie-algebras of K_∞ resp. $\tilde{K}_\infty$ the group $\tilde{K}_\infty$ acts on $\mathfrak{g}, \tilde{\mathfrak{k}}$ via the adjoint action (see 1.1.3) We start from a $(\mathfrak{g}, \tilde{K}_\infty)$ module $\mathfrak{I}_B^G\chi$ and a module $\mathcal{M}_{\lambda,\mathbb{C}}$.

Our goal is to compute the cohomology of the complex (See Chap.III, 4.1.4)

$$\mathrm{Hom}_{\tilde{K}_\infty}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathfrak{I}_B^G\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}). \tag{4.50}$$

There is an obvious condition for the complex to be non zero. The group $Z(\mathbb{R}) \subset \tilde{K}_\infty$ acts trivially on $\mathfrak{g}/\mathfrak{k}$ and hence we see that the complex is trivial unless we have

$$\omega_\chi^{-1} = \lambda_\mathbb{R}|_{Z(\mathbb{R})}$$

we assume that this relation holds.

We will derive a formula for these cohomology modules, which is a special case of a formula of Delorme. It will also be discussed in Chap. III. An element $\omega \in \mathrm{Hom}_{\tilde{K}_\infty}(\Lambda^n(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathfrak{I}_B^G\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}})$ attaches to any n tuple $v_1, \ldots, v_n$ of elements in $\mathfrak{g}/\tilde{\mathfrak{k}}$ an element

$$\omega(v_1, \ldots, v_n) \in \mathfrak{I}_B^G\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}} \tag{4.51}$$

such that $\omega(\mathrm{Ad}(k)v_1, \ldots, \mathrm{Ad}(k)v_n) = k\omega(v_1, \ldots, v_n)$ for all $k \in \tilde{K}_\infty$.

By construction

$$\omega(v_1, \ldots, v_n) = \sum f_\nu \otimes m_\nu \text{ where } f_\nu \in \mathfrak{I}_B^G\chi, m_\nu \in \mathcal{M}_{\lambda,\mathbb{C}}$$

and f_ν is a function in $\mathcal{C}_\infty$ which is determined by its restriction to $\tilde{K}_\infty$ (and this restriction is $\tilde{K}_\infty$ finite). We can evaluate this function at the identity $e_G \in G(\mathbb{R})$ and then

$$\omega(v_1, \ldots, v_n)(e_G) = \sum f_\nu(e) \otimes m_\nu \in \mathbb{C}\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}$$

The $\tilde{K}_\infty$ invariance (4.51) implies that ω is determined by this evaluation at e_G. Let $\tilde{K}_\infty^T = T(\mathbb{R}) \cap \tilde{K}_\infty = Z(\mathbb{R}) \cdot T_c$. Then it is clear that

$$\omega^* : \{v_1, \ldots, v_n\} \mapsto \omega(v_1, \ldots, v_n)(e_G) \tag{4.52}$$

is an element in

$$\omega^* \in \mathrm{Hom}_{\tilde{K}^T_\infty}(\Lambda^n(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathbb{C}\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}) \tag{4.53}$$

and we have: The map $\omega \mapsto \omega^*$ is an isomorphism of complexes $\boxed{\text{iso1}}$

$$\mathrm{Hom}_{\tilde{K}_\infty}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathfrak{I}_B^G\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}) \xrightarrow{\sim} \mathrm{Hom}_{\mathfrak{c}}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathbb{C}\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}) \tag{4.54}$$

The Lie algebra $\mathfrak{g}$ can be written as a sum of $\mathfrak{c}$ invariant submodules

$$\mathfrak{g} = \mathfrak{b} + \tilde{\mathfrak{k}} = \mathfrak{t} + \mathfrak{u} + \tilde{\mathfrak{k}} \tag{4.55}$$

in case B) this sum is not direct, we have $\mathfrak{b} \cap \tilde{\mathfrak{k}} = \mathfrak{t} \cap \tilde{\mathfrak{k}} = \mathfrak{c}$ and hence we get the direct sum decomposition into $\tilde{K}^T_\infty$-invariant subspaces

$$\mathfrak{g}/\tilde{\mathfrak{k}} = \mathfrak{t}/\mathfrak{c} \oplus \mathfrak{u}. \tag{4.56}$$

We get an isomorphism of complexes $\boxed{\text{isodel}}$

$$\mathrm{Hom}_{\tilde{K}_\infty}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathfrak{I}_B^G\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}) \xrightarrow{\sim} \mathrm{Hom}_{\tilde{K}^T_\infty}(\Lambda^\bullet(\mathfrak{t}/\tilde{\mathfrak{k}}), \mathbb{C}\chi \otimes \mathrm{Hom}(\Lambda^\bullet(\mathfrak{u}), \mathcal{M}_{\lambda,\mathbb{C}})) \tag{4.57}$$

the complex on the left is isomorphic to the total complex of the double complex on the right.

Intermission: The theorem of Kostant The next step is the computation of the cohomology of the complex $\mathrm{Hom}(\Lambda^\bullet(\mathfrak{u}), \mathcal{M}_{\lambda,\mathbb{C}})$.

Case A). Our group is $G/\mathbb{Q} = \mathrm{Gl}_2/\mathbb{Q}$. Then $\mathfrak{u} = \mathbb{Q}E_+$ where $E_+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$ and our module $\mathcal{M}_{\lambda,\mathbb{Q}}$ has a decomposition into weight spaces

$$\mathcal{M}_{\lambda,\mathbb{Q}} = \bigoplus_{\nu=1}^{\nu=n-\nu} \mathbb{Q}X^{n-\nu}Y^\nu = \bigoplus_{\mu=-n,\mu\equiv n(2)}^{\mu=n} \mathbb{Q}e_\mu. \tag{4.58}$$

The torus $T^{(1)} = \{\begin{pmatrix} t & 0 \\ 0 & t^{-1} \end{pmatrix}\}$ acts on $e_\mu = X^{n-\nu}Y^\nu$ by

$$\rho_\lambda(\begin{pmatrix} t & 0 \\ 0 & t^{-1} \end{pmatrix})e_\mu = t^\mu e_\mu \tag{4.59}$$

We also have the action of the Lie algebra on $\mathcal{M}_{\lambda,\mathbb{Q}}$ (See section **??**) and by definition we get

$$d(\rho_\lambda)(E_+)e_\mu = E_+e_\mu = \frac{n-\mu}{2}e_{\mu+2} \tag{4.60}$$

Now we can write down our complex $\mathrm{Hom}(\Lambda^\bullet(\mathfrak{u}), \mathcal{M}_{\lambda,\mathbb{C}})$ very explicitly. Let $E_+^\vee \in \mathrm{Hom}(\mathfrak{u}, \mathbb{Q})$ be the element $E_+^\vee(E_+) = 1$ then the complex becomes

$$0 \to \bigoplus_{\mu=-n,\mu\equiv n(2)}^{\mu=n} \mathbb{Q}e_\mu \xrightarrow{d} \bigoplus_{\mu=-n,\mu\equiv n(2)}^{\mu=n} \mathbb{Q}E_+^\vee \otimes e_\mu \to 0 \tag{4.61}$$

where $d(e_\mu) = \frac{n-\mu}{2} E_+^\vee \otimes e_{\mu+2}$. This gives us a decomposition of our complex into two sub complexes

$$\mathrm{Hom}(\Lambda^\bullet(\mathfrak{u}), \mathcal{M}_{\lambda,\mathbb{C}}) = \mathbb{H}^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{Q}}) \oplus AC^\bullet \tag{4.62}$$

where $AC^\bullet$ as acyclic (it has no cohomology) and in

$$\mathbb{H}^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{Q}}) = \{0 \to \mathbb{Q}\, e_n \xrightarrow{d} \mathbb{Q}\, E_+^\vee \otimes e_{-n} \to 0\} \tag{4.63}$$

where the differential d is zero. Hence we get

$$H^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{Q}}) = H^\bullet(\ \mathrm{Hom}(\Lambda^\bullet(\mathfrak{u}), \mathcal{M}_{\lambda,\mathbb{Q}})) = \mathbb{H}^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{Q}}) \tag{4.64}$$

We notice that the torus T acts on $H^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{Q}})$ (The Borel subgroup B acts on the complex $\mathrm{Hom}(\Lambda^\bullet(\mathfrak{u}), \mathcal{M}_{\lambda,\mathbb{Q}})$ but since the Lie algebra cohomology is the derived functor of taking invariants under U (elements annihilated by $\mathfrak{u}$) it follows that this action is trivial on U).

Hence we see that T acts by the character λ on $\mathbb{Q}\, e_n = H^0(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{Q}})$ and by the character $\lambda^- - \alpha = w_0 \cdot \lambda = \lambda^{w_0} - 2\rho$ on $\mathbb{Q}\, E_+^\vee \otimes e_{-n} = H^1(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{Q}})$. Here we see the simplest example of the famous theorem of Kostant which will be discussed in Chap. III 6.1.3.

We discuss the case B). Again we want that our group $G/\mathbb{R} = R_{\mathbb{C}/\mathbb{R}}(\mathrm{Gl}_2/\mathbb{C})$ is a base change from a group $G/\mathbb{Q}$ denoted by the same letter. We need an imaginary quadratic extension $F/\mathbb{Q}$ and put $G/\mathbb{Q} = R_{F/\mathbb{Q}}(\mathrm{Gl}_2/F)$. We choose a dominant weight $\lambda = \lambda_1 + \lambda_2 = n_1\gamma_1 + d_1 \det_1 + n_2\gamma_2 + d_2 \det_2$ and then $\mathcal{M}_{\lambda,F} = \mathcal{M}_{\lambda_1,F} \otimes \mathcal{M}_{\lambda_2,F}$ is an irreducible representation of $G \times_{\mathbb{Q}} F = \mathrm{Gl}_2 \times \mathrm{Gl}_2/F$. Now we have $\mathfrak{u} \otimes F = FE_+^1 \oplus FE_+^2$. Then basically the same computation yields:

The cohomology $H^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,F})$ is equal the complex

$$\mathbb{H}^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,F}) = \{0 \to Fe_{n_1}^{(1)} \otimes Fe_{n_2}^{(2)} \xrightarrow{d} FE_+^{1,\vee} \otimes e_{-n_1}^{(1)} \otimes e_{n_2}^{(2)} \oplus FE_+^{1,\vee} \otimes e_{n_1}^{(1)} \otimes E_+^{2,\vee} \otimes e_{-n_2}^{(2)} \xrightarrow{d} FE_+^{1,\vee} \otimes e_{-n_1}^{(1)} \otimes E_+^{2,\vee} \otimes e_{-n_2}^{(2)} \to 0\} \tag{4.65}$$

where all the differentials are zero. The torus T acts by the weights

$$\lambda \text{ in degree } 0,\ s_1 \cdot \lambda, s_2 \cdot \lambda \text{ in degree } 1,\ w_0 \cdot \lambda \text{ in degree } 2 \tag{4.66}$$

and we have a decomposition into one dimensional weight spaces

$$H^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,F}) = \bigoplus_{w \in W(\mathbb{C})} H^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,F})(w \cdot \lambda)$$

We go back to (4.67) and get a homomorphism of complexes

$$\mathrm{Hom}_{\mathfrak{c}}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathbb{C}\chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}) \to\ \mathrm{Hom}_{\mathfrak{c}}(\Lambda^\bullet(\mathfrak{t}/\tilde{\mathfrak{k}}), \mathbb{C}\chi \otimes \mathbb{H}^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{C}})) \tag{4.67}$$

which induces an isomorphism in cohomology so that finally

$$H^\bullet(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}) \xrightarrow{\sim} H^\bullet(\ \mathrm{Hom}_{\mathfrak{c}}(\Lambda^\bullet(\mathfrak{t}/\tilde{\mathfrak{k}}), \mathbb{C}\chi \otimes H^\bullet(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{C}})) \tag{4.68}$$

and combining this with the results above we get $\boxed{\text{cohlam}}$

Theorem 4.1.1. *If we can find a $w \in W(\mathbb{C})$ such that $\chi^{-1} = w \cdot \lambda_{\mathbb{R}}$ then*

$$H^\bullet(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \chi \otimes \mathcal{M}_{\lambda,\mathbb{C}}) \xrightarrow{\sim} H^{l(w)}(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{C}})(w \cdot \lambda) \otimes \Lambda^\bullet(\mathfrak{t}/\tilde{\mathfrak{k}})^\vee$$

If there is no such w then the cohomology is zero.

Proof. Our torus $T(\mathbb{R}) = \mathfrak{c} \times \{\begin{pmatrix} t & 0 \\ 0 & t^{-1} \end{pmatrix}; \ t \in \mathbb{R}^\times_{>0}\} = \mathfrak{c} \times A$. Hence we see that $\dim \mathfrak{t}/\tilde{\mathfrak{k}} = 1$, and the element $H_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$. Of course we must have that $\chi^{-1} \cdot \lambda_{\mathbb{R}}|_{\mathfrak{c}}$ is the trivial character. The second factor A does acts on $\mathbb{C}\chi$ by the character $\chi(t) = t^z$ and on $H^{l(w)}(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{C}})(w \cdot \lambda)$ by $t \mapsto t^{m(w)}$. Differentiating we get for the complex

$$0 \to H^{l(w)}(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{C}})(w \cdot \lambda) \to \mathbb{C} \otimes H_0^\vee \otimes H^{l(w)}(\mathfrak{u}, \mathcal{M}_{\lambda,\mathbb{C}})(w \cdot \lambda) \to 0 \quad (4.69)$$

where the differential is multiplication by $m(w) + z$. Hence we see that the cohomology is trivial unless $m(w) + z = 0$, but this means $\chi^{-1} = w \cdot \lambda_{\mathbb{R}}$. □

The cohomology of the modules $\mathcal{M}_{\lambda,\mathbb{C}}$, $\mathcal{D}_\lambda$ and the cohomology of unitary modules

Again we start from a dominant character λ. We take the tensor product of the exact sequence (4.36) by $\mathcal{M}_{\lambda^\vee}$ and we get a long exact sequence of $(\mathfrak{g}, K_\infty)$ cohomology modules

$$\begin{array}{c} 0 \to H^0(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee}) \to H^0\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \otimes \mathcal{M}_{\lambda^\vee}) \to H^0(\mathfrak{g}, K_\infty, \mathcal{D}_\lambda \otimes \mathcal{M}_{\lambda^\vee}) \\ \to H^1(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee}) \to H^1\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \otimes \mathcal{M}_{\lambda^\vee}) \to H^1(\mathfrak{g}, K_\infty, \mathcal{D}_\lambda \otimes \mathcal{M}_{\lambda^\vee}) \\ \to H^2(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee}) \to H^2(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \otimes \mathcal{M}_{\lambda^\vee}) \to H^2(\mathfrak{g}, K_\infty, \mathcal{D}_\lambda \otimes \mathcal{M}_{\lambda^\vee}) \\ \to H^3(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee}) \to 0 \end{array} \quad (4.70)$$

We have seen that the modules $\mathcal{D}_\lambda \xrightarrow{\sim} \mathfrak{I}_B^G s_i \cdot \lambda_{\mathbb{R}}$ and hence know all the cohomology in this exact sequence except the the $H^\bullet(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee})$. But then a careful analysis of K_∞ -types shows

Proposition 4.1.6.

$$\begin{array}{c} H^0(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee}) = H^3(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee}) = \mathbb{C}, \\ H^1(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee}) = H^2(\mathfrak{g}, K_\infty, \mathcal{M}_{\lambda,\mathbb{C}} \otimes \mathcal{M}_{\lambda^\vee}) = 0 \\ H^3(\mathfrak{g}, K_\infty, \mathcal{D}_\lambda \otimes \mathcal{M}_{\lambda^\vee}) = H^2(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \otimes \mathcal{M}_{\lambda^\vee}) = 0 \end{array}$$

If $w \in W(\mathbb{C})$ is not $= e, w_0$ (i.e. it is one of the elements of length one) then $\mathfrak{I}_B^G w \cdot \lambda_{\mathbb{R}} \xrightarrow{\sim} \mathcal{D}_\lambda$. Looking at the K_∞ types occurring we see that the semi simple part of the lowest K_∞ -type is $(n_1 + n_2 + 2)\gamma_c$. The K_∞ type of $\mathfrak{g}/\tilde{\mathfrak{k}}$ has highest weight $2\gamma_c$ and $\mathcal{M}_{\lambda,\mathbb{C}}$ has highest weight $(n_1 + n_2)\gamma_c$. This implies that our Lie -algebra complex becomes

$$0 \to 0 \to \ \mathrm{Hom}_{K_\infty}(\Lambda^1(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathfrak{I}_B^G w \cdot \Lambda_{\mathbb{R}}) \xrightarrow{\partial} \ \mathrm{Hom}_{K_\infty}(\Lambda^2(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathfrak{I}_B^G w \cdot \lambda_{\mathbb{R}}) \to 0 \to 0, \quad (4.71)$$

in degree 1 and 2 the spaces are of dimension one and since the cohomology in these degrees is also one dimensional it follows that the boundary operator $\partial = 0$.

4.1.3 The Eichler-Shimura Isomorphism

We want to apply these facts on representation theory to the study of cohomology groups $H^\bullet(\Gamma\backslash X, \mathcal{M}_{\lambda,\mathbb{C}})$ where now Γ is a congruence subgroup of $\mathrm{Gl}_2(\mathbb{Z})$ or $\mathrm{Gl}_2(\mathcal{O})$ where $\mathcal{O}$ is the ring of integers in a imaginary quadratic field. (Discuss also quaternionic case- perhaps)

We start again from a dominant $\lambda = n\gamma + d\det \in X^*(T\times\mathbb{C})$. For every $(\mathfrak{g}, K_\infty)$ invariant embedding $\Psi : \mathfrak{I}_B^G w\cdot\lambda_{\mathbb{R}} \hookrightarrow \mathcal{C}_\infty(\Gamma\backslash G(\mathbb{R}))$ induces a homomorphism

$$\Psi_\Lambda:\ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}), \mathfrak{I}_B^G w\cdot\lambda_{\mathbb{R}}\otimes\mathcal{M}_{\lambda^\vee}) \to\ \mathrm{Hom}_{K_\infty}((\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}, (\mathcal{C}_\infty(\Gamma\backslash G(\mathbb{R})\otimes\mathcal{M}_{\lambda^\vee}) \tag{4.72}$$

We will show in Chap. III that the complex on the right is isomorphic to the de-Rham complex:

$$\mathrm{Hom}_{K_\infty}((\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}, (\mathcal{C}_\infty(\Gamma\backslash G(\mathbb{R})\otimes\mathcal{M}_{\lambda^\vee}) \xrightarrow{\sim} \Omega^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}_{\lambda^\vee}}) \tag{4.73}$$

This de-Rham complex computes the cohomology and hence we get an homomorphism $\boxed{\text{gkdeR}}$

$$\Psi^\bullet : H^\bullet(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G w\cdot\lambda_{\mathbb{R}}\otimes\mathcal{M}_{\lambda^\vee}) \to H^\bullet(\Gamma\backslash X, \tilde{\mathcal{M}_{\lambda^\vee}}\otimes\mathbb{C}) \tag{4.74}$$

We denote by $\omega^{(0)}$ the restriction of the central character of $\mathfrak{I}_B^G w\cdot\lambda_{\mathbb{R}}$ to the subgroup Z_0. (See above Interlude) and we introduce the spaces

$$\begin{array}{ll} \mathcal{E}^{\mathrm{mg}}(\lambda, w, \Gamma) = & \mathrm{Hom}_{(\mathfrak{g},K_\infty)}(\mathfrak{I}_B^G w\cdot\lambda_{\mathbb{R}},\ \mathcal{C}_\infty^{\mathrm{mg}}(\Gamma\backslash G(\mathbb{R}), \omega^(0)) \\ \quad\cup & \\ \mathcal{E}^{(2)}(\lambda, w, \Gamma) = & \mathrm{Hom}_{(\mathfrak{g},K_\infty)}(\mathfrak{I}_B^G w\cdot\lambda_{\mathbb{R}},\ \mathcal{C}_\infty^{(2)}(\Gamma\backslash G(\mathbb{R}), \omega^{(0)})) \end{array} \tag{4.75}$$

where the superscripts mg resp. (2) mean moderate growth resp. square integrable.(Reference). From this we get two maps in cohomology

$$\Phi^? : \mathcal{E}^?(\lambda, w, \Gamma)\otimes H^\bullet(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G w\cdot\lambda_{\mathbb{R}}\otimes\mathcal{M}_{\lambda^\vee}) \to H^\bullet(\Gamma\backslash X, \mathcal{M}_{\lambda^\vee}\otimes\mathbb{C}) \tag{4.76}$$

Of course the module $\mathcal{E}^{(2)}(\lambda, w, \lambda) = 0$ unless $\mathfrak{I}_B^G w\cdot\lambda_{\mathbb{R}}$ has a non trivial quotient module which admits a positive definite quasi unitary $(\mathfrak{g}, K_\infty)$ invariant metric. This means that $\mathcal{E}^{(2)}(\lambda, w, \lambda)\neq 0$ implies that in case B) the coefficients satisfy $\boxed{\text{ul}}$

$$n_1 = n_2,\ \text{i.e.}\lambda = n(\gamma_1+\gamma_2) + d_1\det + d_2\det, \tag{4.77}$$

we will say that λ is unitary if this condition is fulfilled. Then the results in section (4.1.2) yield that these irreducible quasi unitary quotient modules are $\mathcal{D}_\lambda^\pm$ in case A) and $\mathcal{D}_\lambda$ in case B) .

If $n = 0$ then λ extends to a character $\tilde{\lambda} : G \to \mathbb{G}_m$ and $\mathcal{M}_{\lambda,\mathbb{C}}$ is one dimensional we write $\mathcal{M}_{\lambda,\mathbb{C}} = \mathbb{C}[\tilde{\lambda}]$.

In the first two cases we know that

$$\mathcal{E}^{(2)}(\lambda, w, \Gamma) =\ \mathrm{Hom}_{(\mathfrak{g},K_\infty)}(\mathcal{D}_\lambda,\ \mathcal{C}_\infty^{(2)}(\Gamma\backslash G(\mathbb{R}), \omega^{(0)}))$$

We have the fundamental $\boxed{\text{ESI}}$

Theorem 4.1.2. *(Eichler-Shimura Isomorphism) Assume λ unitary, then in degree 1 in case A, (resp. degree 1,2 in case B) the map*

$$\Phi^{(2)} : \mathcal{E}^{(2)}(\lambda, w, \Gamma) \otimes H^{\bullet}(\mathfrak{g}, K_\infty, \mathcal{D}_\lambda \otimes \mathcal{M}_{\lambda^\vee}) \to H^{\bullet}_{!}(\Gamma\backslash X, \mathcal{M}_{\lambda^\vee} \otimes \mathbb{C}) \tag{4.78}$$

is an isomorphism.

If we are in the third case, i.e. $n = 0$, and if $\lambda^2|_{\Gamma\cap Z} = 1$ then $\mathrm{Hom}_{(\mathfrak{g},K_\infty)}(\mathbb{C}[\tilde{\lambda}],\ \mathcal{C}_\infty(G(\mathbb{R}))$ is one dimensional and generated by $\Phi_\lambda : 1 \mapsto \tilde{\lambda}$. The map

$$\mathbb{C}\Phi_\lambda \otimes H^{\bullet}(\mathfrak{g}, K_\infty, \mathbb{C}[\tilde{\lambda}] \otimes \mathbb{C}[\tilde{\lambda}^\vee]) \to H^{\bullet}\Gamma\backslash X, \mathcal{M}_{\lambda^\vee} \otimes \mathbb{C}) \tag{4.79}$$

is an isomorphism in degree zero and zero in all other degrees.

We want to relate this to the classical formulation in case A). The group $\mathrm{Sl}_2(\mathbb{R})$ acts transitively on the upper half plane $\mathbb{H} = \mathrm{Sl}_2(\mathbb{R})/\mathrm{SO}(2)$. For $g = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ and $z \in \mathbb{H}$ we put $j(g, z) = cz + d$. To any

$$\Phi \in \ \mathrm{Hom}_{(\mathfrak{g},K_\infty)}(\mathcal{D}^+_\lambda,\ \mathcal{C}^{(2)}_\infty(\Gamma\backslash G(\mathbb{R}), \omega^{(0)}))$$

we attach a function $f^{\Phi}_{n+2} : \mathbb{H} \to \mathbb{C}$: We write $z = gi$ with $g \in \mathrm{Sl}_2(\mathbb{R})$ and put

$$f^{\Phi}_{n+2}(z) = \Phi(\psi_{n+2})(g)j(g, i)^{n+2} \tag{4.80}$$

An easy calculation shows that f^{Φ}_{n+2} is well defined and holomorphic (slzweineu.pdf)p.25-26) and for $\gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{Sl}_2(\mathbb{Z})$ it satisfies

$$f^{\Phi}_{n+2}(\gamma z) = (cz + d)^{n+2} f^{\Phi}_{n+2}(z) \tag{4.81}$$

The condition that $\Phi(\psi_{n+2})(g)$ is square integrable implies that f_{n+2} is a holomorphic cusp form of weight $n + 2 = k$. It is a special case of the theorem of Gelfand-Graev that this provides an isomorphism

$$\mathrm{Hom}_{(\mathfrak{g},K_\infty)}(\mathcal{D}^+_\lambda,\ \mathcal{C}^{(2)}_\infty(\Gamma\backslash G(\mathbb{R})) \xrightarrow{\sim} S_k(\Gamma) \tag{4.82}$$

where of course $S_k(\Gamma)$ is the space of holomorphic cusp forms for Γ.

We can do the same thing with $\mathcal{D}^-_\lambda$ then we land in the spaces of anti holomorphic cusp forms, these two spaces are isomorphic under conjugation. Combining this with our results above gives the classical formulation of the Eichler-Shimura theorem:

We have a canonical isomorphism

$$S_k(\Gamma) \oplus \overline{S_k(\Gamma)} \xrightarrow{\sim} H^1_{!}\Gamma\backslash X, \mathcal{M}_{\lambda^\vee} \otimes \mathbb{C}) \tag{4.83}$$

$\boxed{\text{Whittloc}}$

Local Whittaker models

We recall some fundamental results from representation theory of groups $\mathrm{Gl}_2(\mathbb{Q}_p)$. Let $F/\mathbb{Q}$ be a finite extension $\mathbb{Q}$. An admissible representation of $\mathrm{Gl}_2(\mathbb{Q}_p)$ is an action of $\mathrm{Gl}_2(\mathbb{Q}_p)$ on a F-vector space V which fulfills the following two additional requirements

a) For any open subgroup $K_p \subset \mathrm{Gl}_2(\mathbb{Z}_p)$ the space of fixed vectors V^{K_p} is finite dimensional.

b) For any $v \in V$ we find an open subgroup $K_p \subset \mathrm{Gl}_2(\mathbb{Z}_p)$ such that $v \in V^{K_p}$.

In addition we want to assume that our module has a central character, this means that the center $Z(\mathbb{Q}_p) = \mathbb{Q}_p^\times$ acts by a character $\omega_V : Z(\mathbb{Q}_p) \to F^\times$.

Such a module is called irreducible if it can not be written as a sum of two non trivial submodules.

We recall - and explain the meaning of - the fundamental fact that each isomorphism class of admissible irreducible modules has a unique Whittaker model. We assume that $F \subset \mathbb{C}$, then we define the (additive) character $\boxed{\text{PSI}}$

$$\psi_p : \mathbb{Q}_p \to \mathbb{C}^\times;\ \psi_p\ :\ a/p^m \mapsto e^{\frac{2\pi i a}{p^m}} \tag{4.84}$$

it is clear that the kernel of ψ_p is $\mathbb{Z}_p$. Since we have $U(\mathbb{Q}_p) = \mathbb{Q}_p$ we can view ψ_p as a character $\psi_p : U(\mathbb{Q}_p) \to \mathbb{C}^\times$. We introduce the space

$$\mathcal{C}_{\psi_p}(\mathrm{Gl}_2(\mathbb{Q}_p)) = \{f : \mathrm{Gl}_2(\mathbb{Q}_p) \to \mathbb{C} | f(ug) = \psi_p(u) f(g)\}$$

where in addition we require that our f is invariant under a suitable open subgroup $K_f \subset \mathrm{Gl}_2(\mathbb{Z}_p.)$ The group $\mathrm{Gl}_2(\mathbb{Q}_p)$ acts on this space by right translation the action is not admissible but satisfies the above condition b) .

Now we can state the theorem about existence and uniqueness of the Whittaker model

Theorem 4.1.3. *For any absolutely irreducible admissible* $\mathrm{Gl}_2(\mathbb{Q}_p)$ *-module V we find a non trivial (of course invariant under* $\mathrm{Gl}_2(\mathbb{Q}_p)$*) homomorphism*

$$\Psi : V \to \mathcal{C}_{\psi_p}(\mathrm{Gl}_2(\mathbb{Q}_p)), \tag{4.85}$$

it is unique up to multiplication by a non zero scalar.

Proof. We refer to the literature. □

An absolutely irreducible $\mathrm{Gl}_2(\mathbb{Q}_p)$ module is called spherical or unramified if it contains a non zero element which is invariant under $\mathrm{Gl}_2(\mathbb{Z}_p)$. In this case it is known that

$$\dim_F(V^{\mathrm{Gl}_2(\mathbb{Q}_p)}) = 1; V^{\mathrm{Gl}_2(\mathbb{Q}_p)} = F\phi_0. \tag{4.86}$$

The one dimensional space $V^{\mathrm{Gl}_2(\mathbb{Q}_p)}$ is of course a module for the Hecke-algebra $\mathcal{H}_p$, hence it defines a homomorphism $\pi_V : \mathcal{H}_p \to F$. The Hecke algebra is generated by the two double cosets

$$T_p = \mathrm{Gl}_2(\mathbb{Z}_p) \begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix} \mathrm{Gl}_2(\mathbb{Z}_p) \text{ and } C_p = \mathrm{Gl}_2(\mathbb{Z}_p) \begin{pmatrix} p & 0 \\ 0 & p \end{pmatrix} \tag{4.87}$$

These two operators act by scalars on $V^{\mathrm{Gl}_2(\mathbb{Q}_p)}$, we write

$$T_p(\psi_0) = \pi_V(T_p)\psi_0 \text{ and } C_p(\psi_0) = \pi_V(C_p)\psi_0 \tag{4.88}$$

The module V is completely determined by these two eigenvalues, of course $\pi_V(C_p) = \omega_V(C_p)$.

We can formulate this a little bit differently. Let π_p an isomorphism type of an absolutely irreducible, admissible $\mathrm{Gl}_2(\mathbb{Q}_p)$ module. Then our theorem above asserts that there is a unique $\mathrm{Gl}_2(\mathbb{Q}_p)$ -module

$$\mathcal{W}(\pi_p) \subset \mathcal{C}_\psi(\mathrm{Gl}_2(\mathbb{Q}_p)) \tag{4.89}$$

with isomorphism-type equal to $\pi_p \times_F \mathbb{C}$. We call this module the Whittaker realization of π_p. If our isomorphism type is unramified then the resulting homomorphism of $\mathcal{H}_p$ to F is also denoted by π_p.

We have the spherical vector $h^{(0)}_{\pi_p} \in \mathcal{W}(\pi_p)^{\mathrm{Gl}_2(\mathbb{Q}_p)}$ which is unique up to a scalar. Since $\mathrm{Gl}_2(\mathbb{Q}_p) = U(\mathbb{Q}_p)T(\mathbb{Q}_p)\mathrm{Gl}_2(\mathbb{Z}_p)$ this spherical vector is determined by its restriction to $T(\mathbb{Q}_p)$. We have a formula for this restriction. First of all we observe that

$$h^{(0)}_{\pi_p}(\begin{pmatrix} p^n & 0 \\ 0 & p^m \end{pmatrix} = \pi_p(C_p^m)h^{(0)}_{\pi_p}(\begin{pmatrix} p^{n-m} & 0 \\ 0 & 1 \end{pmatrix}) \tag{4.90}$$

and the eigenvalue equation gives us the recursion (See Chap. III, 2.4.7) $\boxed{\text{recurs}}$

$$\pi_p(T_p)h^{(0)}_{\pi_p}(\begin{pmatrix} p^n & 0 \\ 0 & 1 \end{pmatrix}) = \pi_(C_p)h^{(0)}_{\pi_p}(\begin{pmatrix} p^{n-1} & 0 \\ 0 & 1 \end{pmatrix}) + \begin{cases} ph^{(0)}_{\pi_p}(\begin{pmatrix} p^{n+1} & 0 \\ 0 & 1) \end{pmatrix}) & \text{if } n \geq 0 \\ 0 & \text{if } n < 0 \end{cases} \tag{4.91}$$

Hence it is clear that we can normalize $h^{(0)}_{\pi_p}(\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}) = 1$, then $h^{(0)}_{\pi_p}(\begin{pmatrix} p^n & 0 \\ 0 & 1 \end{pmatrix}) = 0$ if $n < 0$ and the values for $n > 0$ follow from the recursion.

There is are more elegant writing this recursion. For our unramified π_p we define the local Euler factor $\boxed{\text{Euler}}$

$$L(\pi_p, s) = \frac{1}{1 - \pi_p(T_p)p^{-s} + p\pi_p(C_p)p^{-2s}} \tag{4.92}$$

If we expand this into a power series in p^{-s} then $\boxed{\text{Mellin}}$

$$L(\pi_p, s) = \sum_{n=0}^{\infty} h^{(0)}_{\pi_p}(\begin{pmatrix} p^{n+1} & 0 \\ 0 & 1 \end{pmatrix})p^n p^{-ns} \tag{4.93}$$

We also have a theory of Whittacker models for the irreducible Harish-Chandra modules studied in section 4.1. The unipotent radical $U(\mathbb{R}) = \mathbb{R}$ resp. $U(\mathbb{R}) = \mathbb{C}$. Again we fix characters $\psi_\infty : U(\mathbb{R}) \to \mathbb{C}^\times$ we put

$$\psi_\infty(x) = \begin{cases} e^{-2\pi i x} & \text{in case A)} \\ e^{-2\pi i(x+\bar{x})} & \text{in case B)} \end{cases} \tag{4.94}$$

and as in the p-adic case we define

$$\mathcal{C}_{\psi_\infty}(G(\mathbb{R})) = \{f : G(\mathbb{R}) \to \mathbb{C} | f(ug) = \psi_\infty(u) f(g)\}$$

Then we have again

Theorem 4.1.4. *For any infinite dimensional, absolutely irreducible admissible* $\mathrm{Gl}_2(\mathbb{R})$ *-module V we find a non trivial (of course invariant under* $\mathrm{Gl}_2(\mathbb{R})$*) homomorphism*

$$\Psi : V \to \mathcal{C}_{\psi_\infty}(G(\mathbb{R})), \tag{4.95}$$

This homomorphism is unique up to a scalar. The image of V under the homomorphism Ψ will be denoted by $\tilde{V}$.

Proof. Again we refer to the literature. □

Hence we can say that for any isomorphism class π_∞ of irreducible infinite dimensional Harish-Chandra modules we have a unique Whittaker model $\mathcal{W}(\pi_\infty) \subset \mathcal{C}_{\psi_\infty}(G(\mathbb{R}))$. In the book of Godement we find explicit formulae for these Whittaker functions.

In the case A) the we the two discrete irreducible series representations $\mathcal{D}_\lambda^+, \mathcal{D}_\lambda^-$ attached to a dominant weight λ. We have their Whittaker model

$$\Psi_\pm : \mathcal{D}_\lambda^\pm \hookrightarrow \mathcal{C}_{\psi_\infty}(\mathrm{Gl}_2(\mathbb{R})). \tag{4.96}$$

The group $(\mathrm{Gl}_2(\mathbb{R})$ has the two connected components $\mathrm{Gl}_2(\mathbb{R})^+, \mathrm{Gl}_2(\mathbb{R})^-$,($\det > 0, \det < 0)$ and we have

$$\Psi_+(\mathcal{D}_\lambda^+) = \tilde{\mathcal{D}}_\lambda^+ \text{ is supported on } \mathrm{Gl}_2(\mathbb{R})^+, \tilde{\mathcal{D}}_\lambda^- \text{ is supported on } \mathrm{Gl}_2(\mathbb{R})^- \tag{4.97}$$

Under the isomorphism $\Psi_\pm$ the elements $\psi_{\pm(n+2)}$ (See (**??**) are mapped to functions $\tilde{\psi}_{\pm(n+2)}$. We can normalize $\Psi_\pm$ such that $\boxed{\text{tpsin}}$

$$\tilde{\psi}_{n+2}(\begin{pmatrix} t & 0 \\ 0 & 1 \end{pmatrix}) = \begin{cases} t^{\frac{n}{2}+1} e^{-2\pi t} & \text{if } t > 0 \\ 0 & \text{else} \end{cases} \tag{4.98}$$

and $\tilde{\psi}_{-n-2}$ is given by the corresponding formula.

$\boxed{\text{Whitt}}$

Global Whittaker models, Fourier expansions and multiplicity one

We also have global Whittaker models. To define them we recall some results from Tate's thesis. We define the global character $\psi_1 : U(\mathbb{A})/U(\mathbb{Q}) = \mathbb{A}/\mathbb{Q} \to \mathbb{C}^\times$ as the product

$$\psi(x_\infty, \dots, x_p, \dots) = \psi_\infty(x_\infty) \prod_p \psi_p(x_p),$$

we have to check that ψ is trivial on $U(\mathbb{Q})$. For any $a \in \mathbb{Q}$ we define $\psi^{[a]}(x) = \psi(ax)$, so $\psi = \psi^{[1]}$. In [ ] it is shown that the map

$$\mathbb{Q} \to \ \mathrm{Hom}(\mathbb{A}/\mathbb{Q}, \mathbb{C}^\times); \ a \mapsto \psi^{[a]} \tag{4.99}$$

is an isomorphism between $\mathbb{Q}$ and the character group of $\mathbb{A}/\mathbb{Q}$. Hence we know that for any reasonable function $h : \mathbb{A}/\mathbb{Q} \to \mathbb{C}$ we have a Fourier expansion $\boxed{\text{Fouex}}$

$$h(\underline{u}) = \sum_{a \in \mathbb{Q}} \hat{h}(a)\psi(a\underline{u}) \tag{4.100}$$

where $\hat{h}(a) = \int_{\mathbb{A}/\mathbb{Q}} h(\underline{u})\psi(-a\underline{u})d\underline{u}$, and where $\mathrm{vol}_{d\underline{u}}(\mathbb{A}/\mathbb{Q}) = 1$.

Let us start from a representation π_∞ (an infinite dimensional Harish-Chandra-module) and a homomorphism $\pi_f = \otimes'\pi_p : \otimes'\mathcal{H}_p \to F$ from the unramified Hecke algebra to F.

Then we put

$$\mathcal{C}_\psi(\mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f)) = \{f : \mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f \to \mathbb{C} | f(\underline{u}\underline{g}) = \psi(\underline{u})f(\underline{g})\}$$

this is a module for $\mathrm{Gl}_2(\mathbb{R}) \times \bigotimes' \mathcal{H}_p$ and our results on Whittaker-models imply that we have a unique Whittaker-model

$$\mathcal{W}(\pi) = \mathcal{W}(\pi_\infty) \otimes \mathbb{C}h^{(0)}_{\pi_f} \subset \mathcal{C}_\psi(\mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f) \tag{4.101}$$

for our isomorphism class $\pi = \pi_\infty \times \pi_f$. Here of course $h^{(0)}_{\pi_f} = \otimes h^{(0)}_{\pi_p}$.

We return to Theorem 4.1.2. On the space $\mathcal{C}^{(2)}_\infty(\Gamma\backslash G(\mathbb{R}), \omega^{(0)}))$ we have the action of the unramified Hecke algebra. To see this action we start from the observation that the map $\mathrm{Gl}_2(\mathbb{Q}) \to \mathrm{Gl}_2(\mathbb{A}_f)/K_f$ (Chap. III , 1.5) is surjective and hence

$$\mathrm{Gl}_2(\mathbb{Z})\backslash \mathrm{Gl}_2(\mathbb{R}) \xrightarrow{\sim} \mathrm{Gl}_2(\mathbb{Q})\backslash \mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f \tag{4.102}$$

and hence

$$\mathcal{C}^{(2)}_\infty(\mathrm{Gl}_2(\mathbb{Z})\backslash \mathrm{Gl}_2(\mathbb{R})) = \mathcal{C}^{(2)}_\infty(\mathrm{Gl}_2(\mathbb{Q})\backslash \mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f) \tag{4.103}$$

and the space on the right is a $\mathrm{Gl}_2(\mathbb{R}) \times \bigotimes' \mathcal{H}_p$ module. Now we consider the $\pi = \pi_\infty \times \pi_f$ isotypical submodule $\mathcal{C}^{(2)}_\infty(\mathrm{Gl}_2(\mathbb{Q})\backslash \mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f)(\pi) \subset \mathcal{C}^{(2)}_\infty(\mathrm{Gl}_2(\mathbb{Q})\backslash \mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f)$

We have the famous Theorem which in the case $\Gamma = \mathrm{Sl}_2(\mathbb{Z})$ is due to Hecke $\boxed{\text{multone}}$

Theorem 4.1.5. *If $\mathcal{C}^{(2)}_\infty(\mathrm{Gl}_2(\mathbb{Q})\backslash \mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f)(\pi) \neq 0$ then have a canonical isomorphism*

$$\mathcal{F}_1 : \mathcal{W}(\pi) \xrightarrow{\sim} \mathcal{C}^{(2)}_\infty(\mathrm{Gl}_2(\mathbb{Q})\backslash \mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f)(\pi) \tag{4.104}$$

especially we know that π occurs with multiplicity one.

Proof. We give the inverse of $\mathcal{F}_1$. Given a function $h \in \mathcal{C}^{(2)}_\infty(\mathrm{Gl}_2(\mathbb{Q})\backslash \mathrm{Gl}_2(\mathbb{R}) \times \mathrm{Gl}_2(\mathbb{A}_f)/K_f)(\pi)$ we define

$$h^\dagger((g_\infty, \underline{g}_f)) = \int_{U(\mathbb{Q})\backslash U(\mathbb{A})} h(\underline{u}\underline{g})\overline{\psi(\underline{u})}d\underline{u} \tag{4.105}$$

it is clear that $h^\dagger(g_\infty,\underline{g}_f)\in\mathcal{W}(\pi)$. It follows from the theory of automorphic forms that h is actually in the space of cusp forms, this means that the constant Fourier coefficient $\int_{U(\mathbb{Q})\backslash U(\mathbb{A})}h(\underline{u}\underline{g})d\underline{u}=0$ and hence our Fourier expansion yields ((4.100), evaluated at $u=0$)

$$h(\underline{g})=\sum_{a\in\mathbb{Q}^\times}\int_{U(\mathbb{A})/U(\mathbb{Q})}h(\underline{u}\underline{g})\psi^{[a]}(\underline{u})d\underline{u} \tag{4.106}$$

The measure $d\underline{u}$ is invariant under multiplication by $a\in\mathbb{Q}^\times$ and hence a individual term in the summation is

$$\int_{U(\mathbb{A})/U(\mathbb{Q})}h(\begin{pmatrix}1&\underline{u}\\0&1\end{pmatrix}\underline{g})\psi(\begin{pmatrix}1&a\underline{u}\\0&1\end{pmatrix})d\underline{u}=\int_{U(\mathbb{A})/U(\mathbb{Q})}h(\begin{pmatrix}1&a^{-1}\underline{u}\\0&1\end{pmatrix}\underline{g})\psi(\begin{pmatrix}1&\underline{u}\\0&1\end{pmatrix})d\underline{u} \tag{4.107}$$

Now

$$\begin{pmatrix}1&a^{-1}\underline{u}\\0&1\end{pmatrix}=\begin{pmatrix}a^{-1}&0\\0&1\end{pmatrix}\begin{pmatrix}1&\underline{u}\\0&1\end{pmatrix}\begin{pmatrix}a&0\\0&1\end{pmatrix}.$$

Since h is invariant under the action of $G(\mathbb{Q})$ from the left we find

$$\int_{U(\mathbb{A})/U(\mathbb{Q})}h(\underline{u}\underline{g})\psi^{[a]}(\underline{u})d\underline{u}=h^\dagger(\begin{pmatrix}a&0\\0&1\end{pmatrix}(g_\infty,\underline{g}_f)) \tag{4.108}$$

We evaluate at $\underline{g}=(g_\infty,e)$ then

$$h^\dagger(\begin{pmatrix}a&0\\0&1\end{pmatrix}(g_\infty,e))=h^\dagger(\begin{pmatrix}a_\infty&0\\0&1\end{pmatrix}g_\infty,\begin{pmatrix}\underline{a}_f&0\\0&1\end{pmatrix}) \tag{4.109}$$

For a fixed g_∞ the function $\underline{g}_f\mapsto h^\dagger(g_\infty,\underline{g}_f)$ is up to a factor equal to $h^{(0)}_{\pi_f}=\bigotimes'_p h^{(0)}_{\pi_p}$ and hence we find

$$h^\dagger(\begin{pmatrix}a&0\\0&1\end{pmatrix}(g_\infty,e))=h^\dagger(\begin{pmatrix}a_\infty&0\\0&1\end{pmatrix}g_\infty,e)h^{(0)}_{\pi_f}(\begin{pmatrix}\underline{a}_f&0\\0&1\end{pmatrix}) \tag{4.110}$$

In the case A) the recursion formulae (4.91),(4.93) imply that $h^{(0)}_{\pi_f}(\begin{pmatrix}\underline{a}_f&0\\0&1\end{pmatrix})=0$ unless $a\in\mathbb{Z}$.

We restrict our functions to $\mathrm{Gl}_2^+(\mathbb{R})$, i.e. we take $g_\infty\in\mathrm{Gl}_2(\mathbb{R})^+$ and we consider the representation $\mathcal{D}^+_\lambda$. Then we know that for $h_\infty\in\mathcal{D}^+_\lambda$ the value $h^\dagger(\begin{pmatrix}a_\infty&0\\0&1\end{pmatrix}g_\infty,e)=0$ if $a_\infty<0$ and hence

$$h^\dagger(\begin{pmatrix}a&0\\0&1\end{pmatrix}(g_\infty,e))=h^\dagger(\begin{pmatrix}a_\infty&0\\0&1\end{pmatrix}g_\infty,\begin{pmatrix}\underline{a}_f&0\\0&1\end{pmatrix})=0 \text{ unless } a>0,a\in\mathbb{Z}$$

Our Fourier expansion (4.100) becomes $\boxed{\text{Fexpl}}$

$$h(\underline{g})=\sum_{a=1}^{\infty}h^\dagger(\begin{pmatrix}a&0\\0&1\end{pmatrix}(g_\infty,e))h^{(0)}_{\pi_f}(\begin{pmatrix}\underline{a}_f&0\\0&1\end{pmatrix}) \tag{4.111}$$

□

This is now a few steps of translations the classical Fourier expansion in Hecke.

periods

4.1.4 The Periods

Together with the map $\mathcal{F}_1$ comes the map

$$\tilde{\mathcal{F}}_1 = \mathrm{Id}\otimes\mathcal{F}_1\otimes\mathrm{Id}:\ \mathrm{Hom}_{\tilde{K}_\infty}(\Lambda(\mathfrak{g}/\tilde{\mathfrak{k}}),\mathcal{W}(\pi)\otimes\tilde{\mathcal{M}}_\lambda)\to$$
$$\mathrm{Hom}_{\tilde{K}_\infty}(\Lambda(\mathfrak{g}/\tilde{\mathfrak{k}}),\mathrm{Gl}_2(\mathbb{Q})\backslash\mathcal{C}_\infty(\mathrm{Gl}_2(\mathbb{R})\times\mathrm{Gl}_2(\mathbb{A}_f)/K_f)\otimes\tilde{\mathcal{M}}_\lambda)$$

We choose specific basis elements $\omega^\dagger_\pm\in\ \mathrm{Hom}_{\tilde{K}_\infty}(\Lambda^1(\mathfrak{g}/\mathfrak{k}),\tilde{\mathcal{D}_\lambda}^{\pm}\otimes\mathcal{M}_{\lambda^\vee})$ (in case A) $\omega^\dagger_{1,2}\in\ \mathrm{Hom}_{\tilde{K}_\infty}(\Lambda^{1,2}(\mathfrak{g}/\mathfrak{k}),\tilde{\mathcal{D}_\lambda}\otimes\mathcal{M}_{\lambda^\vee})$ (in case B)):

In case A) we have

$$\mathfrak{g}/\tilde{\mathfrak{k}}=\mathbb{Q}\begin{pmatrix}1&0\\0&-1\end{pmatrix}+\mathbb{Q}\begin{pmatrix}0&1\\1&0\end{pmatrix}=\mathbb{Q}H+\mathbb{Q}V \tag{4.112}$$

If we put $P=\begin{pmatrix}1&0\\0&-1\end{pmatrix}+\begin{pmatrix}0&1\\1&0\end{pmatrix}\otimes i,\bar{P}=\begin{pmatrix}1&0\\0&-1\end{pmatrix}-\begin{pmatrix}0&1\\1&0\end{pmatrix}\otimes i\in\mathfrak{g}/\tilde{\mathfrak{k}}\otimes\mathbb{Q}(i)$ then

$$\mathfrak{g}/\tilde{\mathfrak{k}}\otimes\mathbb{Q}(i)=\mathbb{Q}(i)P\oplus\mathbb{Q}(i)\bar{P}\ \text{ and }\ e(\phi)Pe(-\phi)=e^{2i\phi}P;e(\phi)\bar{P}e(-\phi)=e^{-2i\phi}\bar{P} \tag{4.113}$$

Let $P^\vee,\bar{P}^\vee\in\ \mathrm{Hom}(\mathfrak{g}/\tilde{\mathfrak{k}},\mathbb{Q}(i))$ be the dual basis. Then we check easily that

$$P^\vee(H)=\bar{P}^\vee(H)=\frac{1}{2}\ \text{ and }\ P^\vee(V)=-i\frac{1}{2},\bar{P}^\vee(V)=i\frac{1}{2} \tag{4.114}$$

The module $\mathcal{M}_{\lambda^\vee}\otimes\mathbb{Q}(i)$ decomposes under the action of $\tilde{K}_\infty$ into eigenspaces under $\tilde{K}_\infty$

$$\mathcal{M}_{\lambda^\vee}\otimes\mathbb{Q}(i)=\bigoplus_\nu^n\mathbb{Q}(i)(X+Y\otimes i)^{n-\nu}(X-Y\otimes i)^\nu \tag{4.115}$$

where

$$e(\phi)((X+Y\otimes i)^{n-\nu}(X-Y\otimes i)^\nu)=e^{\pi i(n-2\nu)\phi}\cdot(X+Y\otimes i)^{-n-\nu}(X-Y\otimes i)^\nu.$$

Then we define

$$\omega^\dagger=P^\vee\otimes\tilde{\psi}_{n+2}\otimes(X-Y\otimes i)^n\ ;\ \bar{\omega}^\dagger=\bar{P}^\vee\otimes\tilde{\psi}_{-n-2}\otimes(X+Y\otimes i)^n \tag{4.116}$$

We still have our involution $\mathbf{c}\in\tilde{K}^*_\infty$ and clearly we have $\mathbf{c}\omega^\dagger=i^n\bar{\omega}^\dagger$
(Remember $n\equiv 0\mod 2.$) (Some more words, specific generators)

Now we put OPM

$$\omega^\dagger_+=\frac{1}{2}(\omega^\dagger+i^n\bar{\omega}^\dagger)\ ;\ \omega^\dagger_-=\frac{1}{2}(\omega^\dagger-i^n\bar{\omega}^\dagger) \tag{4.117}$$

In case B) we do basically the same, actually the situation is even simpler because K_∞ is maximal compact in this case, i.e. $K_\infty = K_\infty^*$. The quotient $\mathfrak{g}/\tilde{\mathfrak{k}}$ is a three-dimensional vector space over $\mathbb{Q}$ the group K_∞ acts by the adjoint representation and this gives us the standard three dimensional representation of $K_\infty = U(2)$, which in addition is trivial on the center. (See 4.1.1). This module is given by the highest weight $2\gamma_c$. We t must have $\lambda = n(\gamma + \bar{\gamma}) + ..$, if we want $\mathcal{E}^{(2)}(\lambda, w, \Gamma) \neq 0$, and then the formulae 4.42 and 4.43 imply that for $\bullet = 1, 2$

$$\dim_{\mathbb{C}} \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}), \tilde{\mathcal{D}_\lambda} \otimes \mathcal{M}_{\lambda^\vee}) = 1 \tag{4.118}$$

Now we recall that we have defined a structure of a $R = \mathbb{Z}[\frac{1}{2}]$ module on all the modules on the stage, hence we see that

$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}}), \tilde{\mathcal{D}_\lambda} \otimes \mathcal{M}_{\lambda^\vee}) = \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}})_R, \tilde{\mathcal{D}}_{\lambda R} \otimes \mathcal{M}_{\lambda^\vee R}) \otimes \mathbb{C}, \tag{4.119}$$

here we are a little bit sloppy: The first subscript K_∞ is the compact group and the second subscript is a smooth groups scheme over R. For both choices of $\bullet$ the second term in the above equation is a free R module of rank 1. We choose generators

$$\omega^{\dagger,\bullet} \in \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\tilde{\mathfrak{k}})_R, \tilde{\mathcal{D}}_{\lambda R} \otimes \mathcal{M}_{\lambda^\vee R}).$$

These generators $\omega^{\dagger,1}, \omega^{\dagger,2}$ are well defined up to an element in $R^\times$.

We observe that the same principles applied in the case A) give us $\omega^\dagger_\pm$ as generators.

The inner cohomology with rational coefficients is a semi-simple module under the action of the Hecke algebra (See Theorem 3.2.1). We find a finite Galois-extension $F/\mathbb{Q}$ such that

$$H^\bullet_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F) = \bigoplus_{\pi_f} H^\bullet_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f) \tag{4.120}$$

We assume that $\Gamma = \mathrm{Gl}_2(\mathbb{Z})$, hence the π_f are homomorphisms $\pi_f : \mathcal{H} \to \mathcal{O}_F$. (See ???) In the case A) such an isotypical piece is a direct sum

$$H^\bullet_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f) = H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f)_+ \oplus H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f)_- \tag{4.121}$$

where both summands are of dimension one over F.

In case B) we get

$$H^\bullet_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f) = H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f) \oplus H^2(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f) \tag{4.122}$$

and again the summands are one dimensional.

We can go one step further and consider the spaces (See (????)) $H^\bullet_{!,\,\mathrm{int}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f)_\epsilon$ this are locally free $\mathcal{O}_F$ -modules of rank 1. Then we can cover $\mathrm{Spec}(\mathcal{O}_F)$ by open subsets U_ν such that for $\mathcal{O}_F(U_\nu) = \mathrm{Spec}(\mathcal{O}_F)(U_\nu)$ the modules

$$H^\bullet_{!,\,\mathrm{int}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)(\pi_f)_\epsilon \otimes \mathcal{O}_F(U_\nu))$$

are actually free of rank 1. Here $\epsilon = \pm, \bullet = 1$(resp. $\epsilon = 1, \bullet \in \{1,2\}$) Of course we may assume that these U_ν are invariant under the action of the Galois-group. On the set of π_f which occur in this decomposition we have an action of the Galois group (See (???)) and clearly we have canonical isomorphisms

$$\Phi_{\sigma,\tau} : H^\bullet_{!,\,\mathrm{int}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)({}^\sigma\pi_f)_\epsilon \otimes \mathcal{O}_F(U_\nu)) \xrightarrow{\sim} H^\bullet_{!,\,\mathrm{int}}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda \otimes F)({}^\tau\pi_f)_\epsilon \otimes \mathcal{O}_F(U_\nu)) \tag{4.123}$$

We choose generators $e^\bullet_{\nu,\epsilon}(\pi_f)$ and a simple argument using Hilbert theorem 90 shows that we can assume the consistency condition $\boxed{\text{H90}}$

$$\Phi_{\sigma,\tau}(e^\bullet_{\nu,\epsilon}({}^\sigma\pi_f)) = e^\bullet_{\nu,\epsilon}({}^\tau\pi_f) \tag{4.124}$$

We consider the set Σ_F of embeddings $\iota : F \hookrightarrow \mathbb{C}$, the Galois group $\mathrm{Gal}(F/\mathbb{Q})$ is acting simply transitively on this set. For any $\iota \in \Sigma_F$ we get isomorphisms ($\epsilon = \pm, \bullet = 1$ resp. $\bullet \in \{1,2\}$)

$$\mathcal{F}^\bullet_1(\omega^\dagger_\epsilon) : \mathcal{W}(\pi_f) \otimes_{F,\iota} \mathbb{C} \xrightarrow{\sim} H^\bullet_\epsilon(\Gamma\backslash\mathbb{H}, \mathcal{M}_{\lambda^\vee})(\pi_f) \otimes_{F,\iota} \mathbb{C} \tag{4.125}$$

which is defined by

$$\mathcal{F}^\bullet_1(\omega^\dagger_\epsilon) : h_{\pi_f} \mapsto [\mathcal{F}_1(\omega^\dagger_\epsilon \otimes h_{\pi_f})] \tag{4.126}$$

Since we assume that π_f is unramified everywhere $\mathcal{W}(\pi_f)$ we have the canonical basis element $h^{(0)}_f = \prod_p h^{(0)}_{\pi_p}$ where $h^{(0)}_{\pi_p}$ is defined by the equality 4.93.

Then we define the periods

$$[\mathcal{F}_1\omega^\dagger_\epsilon \otimes h^{(\dagger,0)}_{\pi_f}] = \Omega^\epsilon_{U_\nu}(\pi_f)e^\epsilon_{\pi_f,U_\nu} \tag{4.127}$$

These periods depend of course on the choice of the specific "differential forms" $\omega^\dagger_\epsilon$. But since these $\omega^\dagger_\epsilon$ are well defined up to an element in $\mathcal{O}_F^\times$ we see that $\Omega_{U_\nu}(\pi_f)$ is well defined up to an element in $\mathcal{O}_F(U_\nu)^\times$. Of course we have $\boxed{\text{perunit}}$

$$\frac{\Omega_{U_\nu}(\pi_f)}{\Omega_{U_\mu}(\pi_f)} \in \mathcal{O}_F(U_\nu \cap U_\mu)^\times. \tag{4.128}$$

4.1.5 The Eisenstein cohomology class

In section we claimed the existence of the specific cohomology class $\mathrm{Eis}_n \in H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n)$. In this section we give s construction of this class on transcendental level, i.e. we construct a cohomology class $\mathrm{Eis}(\omega_n) \in H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{C})$ whose restriction to the boundary $H^1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n \otimes \mathbb{C})$ is a given class ω_n.. For the general theory of Eisenstein cohomology we refer to Chapter 9.

We start from our highest weight module $\mathcal{M}_\lambda$ and we observe that by definition we have an inclusion

$$i_0 : \mathfrak{I}^G_B \lambda^{w_0}_{\mathbb{R}} \hookrightarrow \mathcal{C}_\infty(\Gamma^+_\infty\backslash G^+(\mathbb{R}))$$

where

$$\Gamma^+_\infty = \{\begin{pmatrix} t_1 & x \\ 0 & t_1 \end{pmatrix} | x \in \mathbb{Z}\, ; t_1 = \pm 1\}.$$

Therefore we get an isomorphism

$$H^1(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \otimes \mathcal{M}_\lambda \otimes \mathbb{C}) \xrightarrow{\sim} H^1(\Gamma_\infty^+ \backslash \mathcal{M}_\lambda \otimes \mathbb{C}) = H^1(\partial(\Gamma \backslash \mathbb{H}), \mathcal{M}_\lambda \otimes \mathbb{C})$$

The inclusion i_0 sends the module $\mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0}$ into a space of functions which are Γ_∞^+ invariant under left translations. Therefore we get a homomorphism

$$\mathrm{Eis} : \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \to \mathcal{C}_\infty(\Gamma \backslash \mathrm{Sl}_2(\mathbb{R}))$$

if we make it invariant by summation, i.e. we define for $f \in \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0}$ $\boxed{\text{ESeries}}$

$$\mathrm{Eis}(f)(x) = \sum_{\Gamma_\infty^+ \backslash \mathrm{Sl}_2(\mathbb{Z})} f(\gamma x) \tag{4.129}$$

(Here I quote H. Jacquet: "Let us speak about convergence later") This provides a homomorphism

$$\mathrm{Eis}^\bullet : H^1(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \otimes \mathcal{M}_\lambda \otimes \mathbb{C})) \to H^1(\Gamma \backslash \mathbb{H}, \mathcal{M}_\lambda \otimes \mathbb{C}) \tag{4.130}$$

In ??? we wrote down a distinguished generator $\omega_n \in: H^1(\mathfrak{g}, K_\infty, \mathfrak{I}_B^G \lambda_{\mathbb{R}}^{w_0} \otimes \mathcal{M}_\lambda \otimes \mathbb{C})$ and we define

$$\mathrm{Eis}_n = \mathrm{Eis}(\omega_n)$$

Proposition 4.1.7. *The restriction of Eis_n to $H^1(\partial(\Gamma \backslash \mathbb{H}; \mathcal{M}_\lambda \otimes \mathbb{C})$ is the class* $[Y^n]$

Chapter 5

Application to Number Theory

5.1 Modular symbols, $L-$ values and denominators of Eisenstein classes.

5.1.1 Modular symbols attached to a torus in Gl_2.

We construct (resp. relative) cycles in $C_1(\Gamma\backslash X, \underline{\mathcal{M}})$ resp. $C_1(\Gamma\backslash X, \partial(\Gamma\backslash X), \underline{\mathcal{M}})$. Our starting point is a maximal torus $T/\mathbb{Q} \subset G/\mathbb{Q}$ and we assume that it is split over a real quadratic extension $F/\mathbb{Q}$. Then the group of real points

$$T(\mathbb{R}) = \mathbb{R}^\times \times \mathbb{R}^\times$$

act on $\mathbb{H}$ and $\bar{\mathbb{H}}$ and it has two fixed points $r, s \in \mathbb{P}^1(F)$. There is a unique geodesic (half) circle $\bar{C}_{r,s} \subset \bar{\mathbb{H}}$ joining these two points. Then $T(\mathbb{R})$ acts transitively on $C_{r,s} = \bar{C}_{r,s} \setminus \{r, s\}$. We have two cases:

a) The torus $T/\mathbb{Q}$ is split. Then the two points $r, s \in \mathbb{P}^1(\mathbb{Q})$. Here for instance we can take $r = 0, s = \infty$, then the geodesic circle is the line $\{iy, y > 0\}$ and the torus is the standard diagonal split torus.

b) Here $\{r, s\} \in \mathbb{P}^1(F) \setminus \mathbb{P}^1(\mathbb{Q})$, then r, s are Galois-conjugates of each other. Our torus $T/\mathbb{Q}$ is given by a suitable embedding

$$j : R_{F/\mathbb{Q}}(\mathbb{G}_m/F) = T \hookrightarrow \mathrm{Gl}_2/\mathbb{Q}.$$

In case a) we can choose any (differentiable) isomorphism

$$\sigma : [0,1] \xrightarrow{\sim} \bar{C}_{r,s}, \sigma(0) = r, \sigma(1) = s \in \partial(\bar{\mathbb{H}})$$

and for any $m \in \mathcal{M}$ we can consider the image of $\sigma \otimes m \in C_1(\bar{\mathbb{H}}) \otimes \mathcal{M}$ in $C_1(\Gamma\backslash\bar{\mathbb{H}}, \partial(\Gamma\backslash\bar{\mathbb{H}}), \underline{\mathcal{M}})$. By definition this is a cycle and hence we get a homology class

$$[C_{r,s} \otimes m] \in H_1(\Gamma\backslash\bar{\mathbb{H}}, \partial(\Gamma\backslash\bar{\mathbb{H}}), \underline{\mathcal{M}}), \tag{5.1}$$

it is easy to see that it does not depend on the choice of σ.

In case b) we have $T(\mathbb{Q}) \xrightarrow{\sim} F^\times$. Then the group $T(\mathbb{Q}) \cap \Gamma$ is a subgroup of finite index in the group of units $\mathcal{O}_F^\times = \{\epsilon_0\} \times \{\pm 1\}$, where ϵ_0 is a fundamental unit. Hence

$$\Gamma_T = T(\mathbb{Q}) \cap \Gamma = \{\epsilon_T\} \times \mu_T \tag{5.2}$$

where ϵ_T is an element of infinite order and μ_T is trivial or $\{\pm 1\}$. This element ϵ_T induces a translation on $C_{r,s}$. The quotient $C_{r,s}/\Gamma_T$ is a circle. If we pick any point $x \in C_{r,s}$ then $[x, \epsilon_T x] \subset C_{r,s}$ is an interval and as above we can find a $\sigma : [0,1] \xrightarrow{\sim} [x, \epsilon_T x], \sigma(0) = x, \sigma(1) = \epsilon_T x$, As before we can consider the 1-chain $\sigma \otimes m \in C_1(\mathbb{H}) \otimes \mathcal{M}$. Its boundary boundary is the zero chain $\{x\} \otimes m - \{\epsilon_T x\} \otimes m$. If we look at the images in $C_\bullet(\Gamma\backslash\mathbb{H}, \underline{\mathcal{M}})$ then

$$\partial_1(\sigma \otimes m) = \sigma(0) \otimes (m - \epsilon_T m) = r \otimes (m - \epsilon_T m) \tag{5.3}$$

Hence we see that $\sigma \otimes m$ is a 1 -cycle if and only if $m = \epsilon_T m$ and hence $m \in \mathcal{M}^T$. Hence we have constructed homology classes

$$[C_{r,s} \otimes m] \in H_1(\Gamma\backslash\mathbb{H}, \underline{\mathcal{M}}) \text{ for all } m \in \mathcal{M}^{<\epsilon_T>} = \mathcal{M}^T \tag{5.4}$$

5.1.2 Evaluation of cuspidal classes on modular symbols

$\boxed{\text{PDual}}$ Let $\mathcal{M}$ be one of our modules $\mathcal{M}_\lambda$. Let $\mathcal{M}^\vee$ be the dual module of $\mathcal{M}$, then we have the pairings

$$H_1(\Gamma\backslash\mathbb{H}, \underline{\mathcal{M}}) \times H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee) \to \mathbb{Z}$$

$$\text{and} \tag{5.5}$$

$$H_1(\Gamma\backslash\mathbb{H}, \partial(\Gamma\backslash\mathbb{H}), \underline{\mathcal{M}}) \times H^1_c(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee) \to \mathbb{Z}$$

These two pairings are non degenerate if we invert 6 and divide by the torsion on both sides. (See [book]).

We have the surjective homomorphism $H^1_c(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee) \to H^1_!((\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee)$ and over a suitably large finite extension $F/\mathbb{Q}$ we have the isotypical decomposition

$$H^1_!((\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee \otimes F) = \bigoplus_{\pi_f} H^1_!((\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee \otimes F)(\pi_f) \tag{5.6}$$

where the π_f are absolutely irreducible. (See Theorem 3.2.1). We choose an embedding $\iota : K \hookrightarrow \mathbb{C}$ in section 4.1.4 we constructed the isomorphism

$$\mathcal{F}^1_1(\omega^\dagger_\epsilon) : \mathcal{W}(\pi_f) \otimes_{F,\iota} \mathbb{C} \to H^1_{\epsilon,!(}(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee \otimes F)({}^\iota\pi_f) \tag{5.7}$$

The space $\mathcal{W}(\pi_f)$ is a very explicit space. Since we want to stick to the case $K_f = K_f^{(0)}$ it is of dimension one and is generated by the element

$$h^{\dagger,0}_{\pi_f} = \prod_p h^{\dagger,0}_p \in \prod_p \mathcal{W}(\pi_p) \text{ where } h^{\dagger,0}_p(e) = 1 \tag{5.8}$$

Now we want to compute the value

$$< C_{r,s} \otimes m, \mathcal{F}_1^1(\omega_\epsilon^\dagger)(h_{\pi_f}^{\dagger,0}) > . \tag{5.9}$$

This expression is not completely unproblematic. The argument $C_{r,s}$ on the left lives in the relative homology group, hence the argument on the right should be in $H_c^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee \otimes \mathbb{C})$. Of course we can lift the class $\mathcal{F}_1^1(\omega_\epsilon^\dagger)(h_{\pi_f}^{\dagger,0})$ to a class

$$\mathcal{F}_1^1\widetilde{(\omega_\epsilon^\dagger)}(h_{\pi_f}^{\dagger,0}) \in H_c^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}^\vee \otimes \mathbb{C}).$$

Then

$$< C_{r,s} \otimes m, \mathcal{F}_1^1\widetilde{(\omega_\epsilon^\dagger)}(h_{\pi_f}^{\dagger,0}) >$$

makes sense, but the result depends on the lift. But we have $\boxed{\text{paircusp}}$

Proposition 5.1.1. *If $\partial(C_{r,s} \otimes m)$ gives the trivial class in $H_0(\partial(\Gamma\backslash\bar{\mathbb{H}}), \tilde{\mathcal{M}}^\vee \otimes \mathbb{C})$ then $< C_{r,s} \otimes m, \mathcal{F}_1^1\widetilde{(\omega_\epsilon^\dagger)}(h_{\pi_f}^{\dagger,0}) >$ does not depend on the lift, i.e. the value $< C_{r,s} \otimes m, \mathcal{F}_1^1(\omega_\epsilon^\dagger)(h_{\pi_f}^{\dagger,0}) >$ is well defined.*

Proof. This is rather clear, we refer to the systematic discussion in Poi-duality. □

Now we "compute" the value of the pairing. We realized the relative homology class by a $\mathcal{M}$ valued 1-chain $\sigma \otimes m$. The expression is a $\mathcal{M}_{\mathbb{C}}^\vee$ valued differential form. Hence we see - under the assumption that $]\partial(C_{r,s} \otimes m)] = 0$- that

$$< C_{r,s} \otimes m, \mathcal{F}_1^1(\omega_\epsilon^\dagger)(h_{\pi_f}^{\dagger,0}) >= \int_0^1 \mathcal{F}_1^1(\omega_\epsilon^\dagger)(h_{\pi_f}^{\dagger,0}(x)(D_\sigma(x)(\frac{\partial}{\partial x}))dx \tag{5.10}$$

where $D_\sigma(x)$ is the derivative of σ at x.

We consider the special case that T is the standard split diagonal torus, this means that $\{r, s\} = \{0, \infty\}$. Our 1- chain is the map

$$\sigma : [0, \infty] \to \bar{\mathbb{H}} : t \mapsto \begin{pmatrix} t & 0 \\ 0 & 1 \end{pmatrix} i = ti \in \bar{\mathbb{H}} \tag{5.11}$$

We choose for $\sigma : T(\mathbb{R})^{(0)} = \mathbb{R}_{>0}^\times \hookrightarrow [0, \infty]$ and then the integral in the formula above becomes

$$\int_0^\infty \tilde{\mathcal{F}}_1(\omega_\epsilon^\dagger \otimes h_{\pi_f}^{\dagger,0}(e)(t\frac{\partial}{\partial t})(t)\frac{dt}{t} \tag{5.12}$$

and this is now

$$\int_0^\infty \tilde{\mathcal{F}}_1(< \omega_\epsilon^\dagger, H \otimes m > \otimes h_{\pi_f}^{\dagger,0})(t, e))\frac{dt}{t} \tag{5.13}$$

Clearly this expression does not depend on the d in $\lambda = n\gamma + d\det$. Since

$$\rho_\lambda(\begin{pmatrix} t^{-1} & 0 \\ 0 & 1 \end{pmatrix})(X \pm Y \otimes i)^n = \sum_{\nu=0}^{n} \binom{n}{\nu} (\pm i)^{n-\nu} t^{\frac{n}{2}-\nu} X^\nu Y^{n-\nu}, \tag{5.14}$$

we get for $t > 0$

$$\tilde{\mathcal{F}}_1(\omega^\dagger)\begin{pmatrix} t & 0 \\ 0 & 1\end{pmatrix}) =$$

$$\sum_{\nu=0}^n (P^\vee \otimes (\sum_{a=1}^\infty (at)^{n+1-\nu} e^{-2\pi a t} h^{(0)}_{\pi_f}(\begin{pmatrix} a_f & 0 \\ 0 & 1\end{pmatrix})) \otimes \frac{(-i)^{n-\nu}}{a_f^{\frac{n}{2}-\nu}} \binom{n}{\nu} X^\nu Y^{n-\nu}))) \tag{5.15}$$

and for $t < 0$ this expression is zero.

For the conjugate $\bar{\omega}^\dagger$ and again $t > 0$ we get

$$\tilde{\mathcal{F}}_1(\bar{\omega}^\dagger)\begin{pmatrix} t & 0 \\ 0 & 1\end{pmatrix}) =$$

$$\sum_{\nu=0}^n (P^\vee \otimes (\sum_{a=1}^\infty (-at)^{n+1-\nu} e^{2\pi a t} h^{(0)}_{\pi_f}(\begin{pmatrix} a_f & 0 \\ 0 & 1\end{pmatrix})) \otimes \frac{i^{n-\nu}}{a_f^{\frac{n}{2}-\nu}} \binom{n}{\nu} X^\nu Y^{n-\nu}))) \tag{5.16}$$

We recall the definition of $\omega^\dagger_\pm$ (4.117), we fix $m = X^{n-\nu_1}Y^{\nu_1}$ then we find (see (4.8)) for $t > 0$

$$2 < \omega^\dagger_\pm, H \otimes m > \otimes h^{\dagger,0}_{\pi_f})(t,e)) =$$

$$\sum_{a=1}^\infty ((at)^{n+1-\nu_1} e^{-2\pi a t} h^{(0)}_{\pi_f}(\begin{pmatrix} a_f & 0 \\ 0 & 1\end{pmatrix})) \frac{(-i)^{-\nu_1}}{a_f^{\frac{n}{2}-\nu_1}} \pm (-at)^{n+1-\nu_1} e^{2\pi a t} h^{(0)}_{\pi_f}(\begin{pmatrix} a_f & 0 \\ 0 & 1\end{pmatrix})) \frac{i^{n-\nu_1}}{a^{\frac{n}{2}-\nu_1}}) \tag{5.17}$$

Hence we get for our integral

$$\int_0^\infty \mathcal{F}_1^1(< \omega^\dagger_\epsilon, H \otimes X^{n-\nu_1} Y_1^\nu > \otimes h^{\dagger,0}_{\pi_f})(t,e)) \frac{dt}{t} =$$

$$\frac{\Gamma(n+1-\nu_1)}{(2\pi)^{n+1-\nu}} (\sum_{a=1}^\infty (\frac{(-i)^{-\nu_1}}{a_f^{\frac{n}{2}-\nu_1}} h^{(0)}_{\pi_f}(\begin{pmatrix} a_f & 0 \\ 0 & 1\end{pmatrix}) \pm \frac{(-i)^{n-\nu_1}}{a_f^{\frac{n}{2}-\nu_1}} h^{(0)}_{\pi_f}(\begin{pmatrix} a_f & 0 \\ 0 & 1\end{pmatrix}))) \tag{5.18}$$

$$\frac{\Gamma(n+1-\nu_1)}{(2\pi)^{n+1-\nu}} (\sum_{a=1}^\infty (\frac{1}{a_f^{\frac{n}{2}-\nu_1}} h^{(0)}_{\pi_f}(\begin{pmatrix} a_f & 0 \\ 0 & 1\end{pmatrix})((-i)^{-\nu_1} \pm i^{n-\nu_1}).$$

By definition we have

$$\sum_{a=1}^\infty (\frac{(-i)^{-\nu_1}}{a_f^{\frac{n}{2}-\nu_1}} h^{(0)}_{\pi_f}(\begin{pmatrix} a_f & 0 \\ 0 & 1\end{pmatrix}) = L^{\mathrm{coh}}(\pi_f, n+1-\nu_1) \tag{5.19}$$

We put $\mathrm{sg}(\epsilon) = +1$ if $\epsilon = +$and $\mathrm{sg}(\epsilon) = -1$ if $\epsilon = -$, then the factor on the right is $i^{-\nu_1}((-1)^{\nu_1} + \mathrm{sg}(\epsilon)(-1)^{n/2})$.

Then we get for $\nu = 0, 1, \ldots, n$

$$\int_0^\infty \tilde{\mathcal{F}}_1(< \omega^\dagger_\epsilon, H \otimes X^{n-\nu} Y^\nu > \otimes h^{\dagger,0}_{\pi_f})(t,e)) = \begin{cases} \Lambda^{\mathrm{coh}}(\pi, n+1-\nu) & \text{if } (-1)^{\frac{n}{2}-\nu} = \mathrm{sg}(\epsilon) \\ 0 & \text{else} \end{cases} \tag{5.20}$$

In the case that $\nu \neq 0, n$ we know that $\partial(C_{0,\infty} \otimes X^{n-\nu}Y^{\nu})$ is a torsion element in $H^0(\partial(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}})$ and therefore the value of the integral is also the evaluation of the cohomology class $\mathcal{F}_1^1(\omega_\epsilon^\dagger)(h_{\pi_f}^{\dagger,0})$ on a integral homology class. we get

$$< C_{0,\infty} \otimes X^{\nu}Y^{n-\nu}, \mathcal{F}_1^1(\omega_\epsilon^\dagger)(h_{\pi_f}^{\dagger,0}) >= \Lambda^{\mathrm{coh}}(\pi, n+1-\nu) \tag{5.21}$$

In section 4.1.4 we defined the periods $\Omega^{\epsilon}_{U_\nu}(\pi_f)$, we then know that

$$\frac{1}{\Omega^{\epsilon}_{U_\nu}(\pi_f)}\mathcal{F}_1^1(\omega_\epsilon^\dagger)(h_{\pi_f}^{\dagger,0}) \in H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathcal{O}_F(U_\nu)) \tag{5.22}$$

and hence we can conclude for $\nu \neq 0, n$ $\boxed{\text{ratint}}$

$$\frac{1}{\Omega^{\epsilon}_{U_\nu}(\pi_f)}\Lambda^{\mathrm{coh}}(\pi, n+1-\nu) \in \mathcal{O}_F(U_\nu) \tag{5.23}$$

This argument fails if $\nu = 0, n$ because $\partial(C_{0,\infty} \otimes X^n) = \infty \otimes (X^n - Y^n)$ is not a torsion class in $H_0(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_\lambda)$ (See section 3.2). We apply the Manin-Drinfeld principle to show that the rationality statement also holds for $\nu = 0, n$ be we will get a denominator.

We pick a prime p then we know that the class $[\partial(C_{0,\infty} \otimes X^n)]$ is an eigenclass modulo torsion for T_p, i.e.

$$T_p([\partial(C_{0,\infty} \otimes X^n]) = (p^{n+1}+1)[\partial(C_{0,\infty} \otimes X^n)] \tag{5.24}$$

This implies that $\partial(T_p([\mathbb{C}_{0,\infty} \otimes X^n]) - (p^{n+1}+1)[(C_{0,\infty} \otimes X^n]))$ is a torsion class, hence we can apply proposition 5.1.1 and get that the value of the pairing is equal to the integral against the modular symbol. If we exploit the adjointness formula for the Hecke operator then get

$$< T_p([\mathbb{C}_{0,\infty} \otimes X^n]) - (p^{n+1}+1)[(C_{0,\infty} \otimes X^n]), \mathcal{F}_1^1(\omega_\epsilon^\dagger \otimes h_{\pi_f}^{\dagger,0}) >$$

$$= \int_0^\infty (< C_{0,\infty} \otimes X^n, \mathcal{F}_1^1(\omega_\epsilon^\dagger \otimes T_p(h_{\pi_f})^{\dagger,0}) > -(p^{n+1}+1) < C_{0,\infty} \otimes X^n, \mathcal{F}_1^1(\omega_\epsilon^\dagger) \otimes ((h_{\pi_f}^{\dagger,0}) >)) \frac{dt}{t} \tag{5.25}$$

We have $T_p(h_{\pi_f}^{\dagger,0}) = a_p h_{\pi_f}^{\dagger,0}$ where $a_p \in \mathcal{O}_F$ and hence we get

$$\begin{aligned} &< T_p([\mathbb{C}_{0,\infty} \otimes X^n]) - (p^{n+1}+1)[(C_{0,\infty} \otimes X^n]), \mathcal{F}_1^1(\omega_\epsilon^\dagger \otimes h_{\pi_f}^{\dagger,0}) > \\ &\qquad = (a_p - (p^{n+1}+1))\Lambda^{\mathrm{coh}}(\pi_f, n+1) \end{aligned} \tag{5.26}$$

It is again the Manin-Drinfeld principle that tells us that for almost all primes p the number $a_p - (p^{n+1}+1) \neq 0$. More precisely we know that the greatest common divisor of these numbers is the numerator

$$Z(n) = \text{numerator}(\zeta(-1-n)) \tag{5.27}$$

This gives us a modified rationality-integrality assertion: For $\nu = n+1, 0$ we have $\boxed{\text{ratintE}}$

$$\frac{1}{\Omega^{\epsilon}_{U_\nu}(\pi_f)}\Lambda^{\mathrm{coh}}(\pi, \nu) \in \frac{1}{Z(n)}\mathcal{O}_F(U_\nu) \tag{5.28}$$

These rationality results go back to Manin and Shimura, In principle we may say that also the integrality assertion goes back to these authors, but here we have to take into account the fine tuning of the periods. (Deligne conjecture?)

5.1.3 Evaluation of Eisenstein classes on capped modular symbols

We have seen that $\boxed{\text{MDEis}}$

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{Q}) = H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n \otimes \mathbb{Q}) \oplus \mathbb{Q}\mathrm{Eis_n} \tag{5.29}$$

where $\mathrm{Eis_n}$ is defined by the two conditions

$$r(\mathrm{Eis_n}) = [Y^n] \text{ and } T_p(\mathrm{Eis_n}) = (p^{n++1} + 1)\mathrm{Eis_n}, \tag{5.30}$$

for all Hecke operators T_p, in our special situation it suffices to check the second condition for $p = 2$. In (???) we raised the question to determine the denominator of the class $\mathrm{Eis_n}$, i.e. we want to determine the smallest integer $\Delta(n) > 0$ such that $\Delta(n)\mathrm{Eis_n}$ becomes an integral class.

To achieve this goal we compute the evaluation of $\mathrm{Eis_n}$ on the first homology group, i.e we compute the value $< c, \mathrm{Eis_n} >$ for $c \in H_1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n^\vee)$. We have the exact sequence

$$H_1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee) \xrightarrow{j} H_1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n^\vee) \to H_1(\Gamma\backslash\mathbb{H}, \partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee) \xrightarrow{\delta} H_0(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee) \tag{5.31}$$

It follows from the construction of $\mathrm{Eis_n}$ that $< c, \mathrm{Eis_n} >\in \mathbb{Z}$ for all the elements the image of j. Therefore we only have to compute the values $< \tilde{c}_\nu, \mathrm{Eis_n} >$, where $\tilde{c}_\mu$ are lifts of a system of generators $\{c_\mu\}$ of $\ker(\delta)$.

In our special case the elements $C_{0,\infty} \otimes e_\nu^\vee$, where $\nu = 0, 1 \ldots, n$ form a set of generators of $H_1(\Gamma\backslash\mathbb{H}, \partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee)$. (Diploma thesis Gebertz). We observe:

The boundary of the element $C_{0,\infty} \otimes e_n^\vee (= \pm C_{0,\infty} \otimes e_0^\vee)$ is an element of infinite order in $H^0(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee)$,

The boundary of an elements $C_{0,\infty} \otimes e_\nu^\vee$ with $0 < \nu < n$ are torsion elements in $H^0(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee)$, This implies

Proposition 5.1.2. *The elements* $C_{0,\infty} \otimes m \in H_1(\Gamma\backslash\mathbb{H}, \partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee)$ *with* $\partial(C_{0,\infty} \otimes m) = 0$ *are of the form*

$$c = C_{0,\infty} \otimes (\sum_{\nu=1}^{\nu=n-1} a_\nu e_\nu^\vee); \quad \textit{with } a_\nu \in \mathbb{Z}$$

Now it seems to be tempting to choose for our our generators above the $C_{0,\infty} \otimes e_\nu^\vee$, but this is not possible because for $\delta(C_{0,\infty} \otimes e_\nu^\vee)$ is not necessarily zero, it is only a torsion element. So we see that it is not clear how to find a suitable system of generators.

To overcome this difficulty we use the Hecke operators. If we want to determine the denominator $\Delta(n)$ we can localize, i.e. for each prime p we have to determine the highest power $p^{d(n,p)}$ which divides $\Delta(n)$. As usual we write $d(n,p) = \mathrm{ord}_p(\Delta(n))$. We replace the ring $\mathbb{Z}$ by its localization $\mathbb{Z}_{(p)}$ and replace all our cohomology and homology groups by he localized groups. In other words we have to check we have to find a set of generators $\{\tilde{c}_\nu\}_\mu \subset H_1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee \otimes \mathbb{Z}_{(p)})$ and compute the denominator $< \tilde{c}_\nu,\ \mathrm{Eis}_n >\in \mathbb{Z}_{(p)}$.

It follows from proposition 3.3.1that for $0 < \nu < n$ the torsion element $\partial(c) = \partial(C_{0,\infty} \otimes (\sum_{\nu=1}^{\nu=n-1} a_\nu e_\nu^\vee))$ is annihilated by a sufficiently high power of the Hecke operator T_p^m and hence we see that $T_p^m(c)$ can be lifted to an element $\widetilde{T_p^m(c)} \in H_1(\partial(\Gamma\backslash\mathbb{H}), \tilde{\mathcal{M}}_n^\vee \otimes \mathbb{Z}_{(p)})$. Now

$$< \widetilde{T_p^m(c)},\ \text{Eis}_n >=< c, T_p^m(\ \text{Eis}_n) >= (p^{n+1}+1)^m < c,\ \text{Eis}_n > \tag{5.32}$$

and hence $\text{ord}_p(< \widetilde{T_p^m(c)},\ \text{Eis}_n >) = \ \text{ord}_p(< c,\ \text{Eis}_n >)$. Hence we get

Proposition 5.1.3. *If ν runs from 1 to $n-1$ and if $T_p^m(\widetilde{C_{0,\infty} \otimes e_\nu^\vee})$ is any lift of $T_p^m(e_\nu^\vee)$ then*

$$d(n,p) = -\min\big(\min_\nu(\ ord_p(< T_p^m(\widetilde{C_{0,\infty} \otimes e_\nu^\vee}),\ Eis_n >)), 0\big)$$

Proof. This is now obvious. □

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5.1.4 The capped modular symbol

Therefore we have to compute $< T_p^m(\widetilde{C_{0,\infty} \otimes e_\nu^\vee}),\ \text{Eis}_n >)$. At this point some meditation is in order. Our cohomology class Eis_n is represented by a closed differential form $\text{Eis}(\omega_n)$ (See (???)) and this differential form lives on $\Gamma\backslash\mathbb{H}$ a hence provides a cohomology class in $\Gamma\backslash\mathbb{H}$. But we know that the inclusion provides an isomorphism

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_n) \xrightarrow{\sim} H^1(\Gamma\backslash\bar{\mathbb{H}}, \tilde{\mathcal{M}}_n)$$

and since $T_p^m(\widetilde{C_{0,\infty} \otimes e_\nu^\vee}) \in H_1(\Gamma\backslash\bar{\mathbb{H}}, \tilde{\mathcal{M}}_n)$ we can evaluate the cohomology class Eis_n on the cycle. But we want get this value $< T_p^m(\widetilde{C_{0,\infty} \otimes e_\nu^\vee}),\ \text{Eis}_n >$ by integration of the differential form against the cycle. This is a little bit problematic because the cycle has non trivial support in $\partial(\Gamma\backslash\mathbb{H})$, and on this circle at infinity the differential form is not really defined.

There are certainly several ways out of this dilemma. One possibility is to deform the cycle $T_p^m(\widetilde{C_{0,\infty} \otimes e_\nu^\vee})$ and "pull" it into the interior $\Gamma\backslash\mathbb{H}$. The cycle is the sum of two 1-chains:

$$T_p^m(\widetilde{C_{0,\infty} \otimes e_\nu^\vee}) = C_{0,\infty} \otimes m_\nu + [\infty, T\infty] \otimes P_\nu$$

(recall definition of Borel-Serre construction from earlier chapters) where

$$\partial(C_{0,\infty} \otimes m_\nu) = \infty \otimes (m_\nu - wm_\nu) + \infty \otimes (1-T)P_\nu = 0$$

Recall that $C_{0,\infty}$ is the continuous extension of $t \mapsto \begin{pmatrix} t & 0 \\ 0 & 1 \end{pmatrix} i$ from $\mathbb{R}_{>0}^\times$ to$\mathbb{H}$ to a map from $[0,\infty] \to \bar{\mathbb{H}}$. We choose a sufficiently large $t_0 \in \mathbb{R}_{>0}^\times$ and restrict $C_{0,\infty}$ to $[t_0^{-1}, t_0]$ we get the one chain $C_{0,\infty}(t_0) \otimes m_\nu$. The boundary of this 1-chain is $\partial(C_{0,\infty}(t_0) \otimes m_\nu) = t_0 \otimes (m_\nu - wm_\nu)$. Now we can do at this level the same as at infinity we get a 1-cycle

$$\widetilde{C_{0,\infty}(t_0) \otimes m_\nu} = C_{0,\infty}(t_0) \otimes m_\nu + [t_0, Tt_0] \otimes P_\nu$$

This 1-cycle clearly defines the same class as $T_p^m(\widetilde{C_{0,\infty}\otimes e_\nu^\vee})$ and since it is a cycle in $C_1(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}})$ we get

$$< T_p^m(\widetilde{C_{0,\infty}\otimes e_\nu^\vee}),\ \mathrm{Eis}_n >= \int_{C_{0,\infty}(t_0)\otimes m_\nu+[t_0,Tt_0]\otimes P_\nu} \mathrm{Eis}_n \tag{5.33}$$

The value of this integral does not depend on t_0 and we check easily that for both summands the limit for $t_0\to\infty$ exists. We find that $\boxed{\text{Nenner1}}$

$$< T_p^m(\widetilde{C_{0,\infty}\otimes e_\nu^\vee}),\ \mathrm{Eis}_n >=$$

$$\int_0^\infty < T_p^m(C_{0,\infty}\otimes e_\nu^\vee),\ \mathrm{Eis}_n > \tfrac{dt}{t} + \lim_{t_0\to\infty}\int_0^1 < [it_0, it_0+x]\otimes P_\nu,\ \mathrm{Eis}_n > dx \tag{5.34}$$

and For the first integral we have

$$\int_0^\infty < T_p^m(C_{0,\infty}\otimes e_\nu^\vee),\ \mathrm{Eis}_n > \frac{dt}{t} = (1+p^{n+1})^m\int_0^\infty < C_{0,\infty}\otimes e_\nu^\vee,\ \mathrm{Eis}_n > \frac{dt}{t}$$

and (handwritten notes page 49)

$$\int_0^\infty < C_{0,\infty}\otimes e_\nu^\vee,\ \mathrm{Eis}_n > \frac{dt}{t} = \frac{\zeta(-\nu)\zeta(\nu-n)}{\zeta(-1-n)} \tag{5.35}$$

remember this holds for $0<\nu<n$.

For the second term we have to observe that it depends on the choice of P_ν. We can replace P_ν by $P_\nu+V$ where $V^T=V$. (This means of course that $V=aX^n$) Then $[V]\in H^0(\partial(\Gamma\backslash\mathbb{H}),\tilde{\mathcal{M}}_\lambda)$ and

$$\lim_{t_0\to\infty}\int_0^1 < [it_0, it_0+x]\otimes(P_\nu+V),\ \mathrm{Eis}_n > dx = \lim_{t_0\to\infty}\int_0^1 < [it_0, it_0+x]\otimes P_\nu,\ \mathrm{Eis}_n > dx + < V,\omega_n > .$$

Therefore the second term is only defined up to a number in $\mathbb{Z}_{(p)}$ but this is ok because we are interested in the p-denominator in (5.34).

We have to evaluate the expression $< [it_0, it_0+x]\otimes(P_\nu+V),\ \mathrm{Eis}_n >$. Using the formula (8.2) we find

$$< [it_0, it_0+x]\otimes(P_\nu+V),\ \mathrm{Eis}_n >=< \begin{pmatrix} t_0 & x\\ 0 & 1\end{pmatrix} P_\nu,\ \mathrm{Eis}(\omega_n)(E_+)(\begin{pmatrix} t_0 & x\\ 0 & 1\end{pmatrix} > \tag{5.36}$$

We know that for $t_0>>1$ the Eisenstein series is approximated by its constant term, i.e.

$$\mathrm{Eis}(\omega_n)(E_+)(\begin{pmatrix} t_0 & x\\ 0 & 1\end{pmatrix}) = t_0^{-n}Y^n + O(e^{-t_0}) \tag{5.37}$$

On the other hand we can write $P_\nu(X,Y)=\sum p_\mu^{(\nu)}X^{n-\mu}Y^\mu$ with $p_{\nu,\mu}\in\mathbb{Z}$. Then

$$\begin{pmatrix} t_0 & x\\ 0 & 1\end{pmatrix} P_\nu = t_0^n p_0^{(\nu)}X^n + \dots \tag{5.38}$$

and

$$< \begin{pmatrix} t_0 & x \\ 0 & 1 \end{pmatrix} P_\nu,\ \mathrm{Eis}(\omega_n)(E_+)(\begin{pmatrix} t_0 & x \\ 0 & 1 \end{pmatrix}) >= p_0^{(\nu)} + O(e^{-t_0}) \tag{5.39}$$

and hence we see that the limit exists and we get

$$\lim_{t_0\to\infty} \int_0^1 < [it_0, it_0 + x] \otimes (P_\nu + V),\ \mathrm{Eis}_n > dx = p_0^{(\nu)} = P_\nu(1,0) \tag{5.40}$$

and hence we have the final formula

$$< T_p^m(\widetilde{C_{0,\infty} \otimes e_\nu^\vee}),\ \mathrm{Eis}_n >= \frac{\zeta(-\nu)\zeta(\nu-n)}{\zeta(-1-n)} + P_\nu(1,0) \mod \mathbb{Z}_{(p)}. \tag{5.41}$$

Therefore we have to compute $P_\nu(1,0) \mod \mathbb{Z}_{(p)}$. Recall that for any $\nu, \nu \neq 0, n$ we have to choose a very large $m > 0$ such that the zero chain $T_p^m(e_\nu^\vee)$ is homologous to

$$T_p^m(e_\nu^\vee) \sim \{\infty\} \otimes L_\nu = \{\infty\} \otimes (1-T)Q_\nu \tag{5.42}$$

with $Q_\nu \in \mathcal{M}_n^\vee$. Then we find $P_\nu = Q_\nu \pm Q_{n+1-\nu}$.

Hence we have to compute $T_p^m(e_\nu^\vee)$. A straightforward but lengthy computation yields

$$Q_\nu(1,0) = \begin{cases} 0 & \text{if } (p-1) \not| \nu+1 \\ \frac{1}{p^{\frac{\nu+1}{p-1}}} & \text{else} \end{cases} \tag{5.43}$$

Now we are ready to compute $d(n,p)$, it is the maximum over all ν $\boxed{\text{denomest}}$

$$-\ \mathrm{ord}_p(\frac{\zeta(-\nu)\zeta(\nu-n)}{\zeta(-1-n)} - (Q_\nu(1,0) + Q_{n-\nu}(1,0)) \mod \mathbb{Z}_{(p)}). \tag{5.44}$$

We have to distinguish cases

I) We have $(p-1) \not| \nu+1$ and $(p-1) \not| n+1-\nu$. In this case $Q_\nu(1,0) = Q_{n+1-\nu}(1,0) = 0$ and

$$-\ \mathrm{ord}_p(\frac{\zeta(-\nu)\zeta(\nu-n)}{\zeta(-1-n)}) = -\ \mathrm{ord}_p((\zeta(-\nu)\zeta(\nu-n)) + \ \mathrm{ord}_p(\zeta(-1-n)) \tag{5.45}$$

II) The number $p-1$ divides exactly on of the numbers $\nu+1$ or $n+1-\nu$ In this case let us assume that it divides $\nu+1$ and let us write $\nu+1 = p^{\alpha-1}\nu_0$, with $p^{\alpha-1}||\nu+1$. Then the p-denominator of $\zeta(-\nu)$ is p^α. Then $\nu - n - 1 \equiv -n-1 \mod (p-1)p^{\alpha-1}$ and hence it follows from the Kummer congruences that we can write

$$\zeta(\nu-n) = \zeta(-n-1) + p^\alpha Z(\nu,n)\ ;\ \text{where } Z(\nu,n) \in \mathbb{Z}_{(p)} \tag{5.46}$$

and then

$$\frac{\zeta(-\nu)\zeta(\nu-n)}{\zeta(-1-n)} = \zeta(-\nu)(1 + p^\alpha \frac{Z(\nu,n)}{\zeta(-1-n)}) \tag{5.47}$$

The theorem of -von Staudt-Clausen tells us that

$$\zeta(-\nu) = \frac{-1}{p^{\frac{\nu}{p-1}}} + v \text{ with } v \in \mathbb{Z}_{(p)} \tag{5.48}$$

and hence the left hand side in the above equation becomes

$$\frac{-1}{p^{\frac{\nu}{p-1}}} + v - \frac{-p^\alpha}{p^{\frac{\nu}{p-1}}}\frac{Z(\nu,n)}{\zeta(-1-n)} + vp^\alpha \frac{Z(\nu,n)}{\zeta(-1-n)} \tag{5.49}$$

We have to subtract $(Q_\nu(1,0)+Q_{n-\nu}(1,0))$ from this expression. Then $Q_\nu(1,0)$ cancels against the first term in the above expression, and $Q_{n-\nu}(1,0) \in \mathbb{Z}_{(p)}$. Hence we see that in equation (5.44) we have to compute

$$-\operatorname{ord}_p\Big(-\frac{-p^\alpha}{p^{\frac{\nu}{p-1}}}\frac{Z(\nu,n)}{\zeta(-1-n)} + vp^\alpha \frac{Z(\nu,n)}{\zeta(-1-n)}\Big) \tag{5.50}$$

By definition we have $\alpha > 0$ and by definition the factor in front of the first term is a unit we see that for this ν the expression in (5.44) is

$$-\operatorname{ord}_p(\zeta(-1-n)) + \operatorname{ord}_p(Z(\nu,n)) = -\operatorname{ord}_p(\zeta(-1-n)) + \operatorname{ord}_p(\zeta(\nu-n))$$

III) We have $p-1|\nu+1$ and $p-1|n+1-\nu$ In this case an elementary computation shows that expression in (5.44) is $\mathbb{Z}_{(p)}$, i.e. it is a p-integer. To see this we write $\nu+1=(p-1)xp^{a-1}, n+1-\nu=(p-1)yp^{b-1}$ with $a>0, b>0$ and x,y prime to p. We assume $a \le b$ and compute

$$\frac{\zeta(1-(p-1)xp^{a-1})\zeta(1-(p-1)yp^{b-1})}{\zeta(1-(p-1)p^{a-1}(x+yp^{b-a}))} \mod \mathbb{Z}_{(p)} \tag{5.51}$$

For a value $\zeta(1-m)$ with $p-1|m$ we write $m=(p-1)xp^{k-1}$ with $(x,p)=1$. We apply again the von Staudt-Clausen theorem

$$\zeta(1-m) = \zeta(1-(p-1)xp^{k-1} = -\frac{1}{xp^k} + Z(x) \text{ where } Z(x) \in \mathbb{Z}_{(p)}$$

In our case this gives -let us assume $a<b$ - for our expression above

$$\frac{-\frac{1}{(xp^a} + Z(x))(-\frac{1}{(yp^b} + Z(y))}{-\frac{1}{(x+yp^{b-a})p^a} + Z(x+yp^{b-a}))} = -\frac{(x+yp^{b-a})(\frac{1}{x}+p^aZ(x))(\frac{1}{yp^b}+Z(y))}{1+p^a(x+yp^{b-a})Z(x+p^{b-a}y)} \tag{5.52}$$

The denominator is a unit, we need to know it modulo p^b, the numerator is a sum of eight terms we can forget all the terms in $\mathbb{Z}_{(p)}$. Then the above expression simplifies

$$\frac{\frac{1}{yp^b} + \frac{1}{xp^a} + \frac{p^{a-b}xZ(x)}{y}}{1+p^axZ(x+yp^{b-a})} \tag{5.53}$$

We want this to be equal to $\frac{1}{yp^b}+\frac{1}{xp^a}$. Hence we have to verify the equality

$$\frac{1}{yp^b}+\frac{1}{xp^a}+\frac{p^{a-b}xZ(x)}{y}=(\frac{1}{yp^b}+\frac{1}{xp^a})(1+p^axZ(x+yp^{b-a})) \tag{5.54}$$

and this comes down to

$$p^{a-b}\frac{xZ(x)}{y}\equiv p^{a-b}\frac{xZ(x+yp^{b-a})}{y} \mod \mathbb{Z}_{(p)} \tag{5.55}$$

and this means

$$Z(x)\equiv Z(x+yp^{b-a}) \mod p^{b-a}$$

and this congruence is easy to verify.

Basically the same argument works if $a=b$. Then it can happen that $x+y\equiv 0 \mod p$. Then we have to write $x+y=p^cz$. Then (5.52) changes into

$$\frac{(-\frac{1}{xp^a}+Z(x))(-\frac{1}{yp^a}+Z(y))}{-\frac{1}{zp^{a+c}}+Z(z))}=-\frac{zp^c(\frac{1}{x}+p^aZ(x))(\frac{1}{yp^a}+Z(y))}{1+p^{a+c}zZ(z)}. \tag{5.56}$$

We ignore the denominator then the only non integral term is

$$(x+y)\frac{1}{x}\frac{1}{yp^a}=\frac{1}{xp^a}+\frac{1}{yp^a}$$

This is now essentially the proof of (3.49), i.e.

Theorem 5.1.1. *If $\Gamma=Sl_2(\mathbb{Z})$ then the denominator of the Eisensteinclass in $H^1(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}_n)$ is the numerator of $\zeta(-1-n)$*

The Deligne-Eichler-Shimura theorem

In this section the material is not presented in a satisfactory form. One reason is that it this point we should start using the language of adeles, but there are also other drawbacks. So in a final version of these notes this section probably be removed.

Begin of probably removed section

In this section I try to explain very briefly some results which are specific for Gl_2 and a few other low dimensional algebraic groups. These results concern representations of the Galois group $\mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ which can be attached to irreducible constituents Π_f in the cohomology. These results are very deep and reaching a better understanding and more general versions of these results is a fundamental task of the subject treated in these notes. The first cases have been tackled by Eichler and Shimura, then Ihara made some contributions and finally Deligne proved a general result for $\mathrm{Gl}_2/\mathbb{Q}$.

We start from the group $G=\mathrm{Gl}_2/\mathbb{Q}$, this is now only a reductive group and its centre is isomorphic to $\mathbb{G}_m/\mathbb{Q}$. Its group of real points is $\mathrm{Gl}_2(\mathbb{R})$ and the centre $\mathbb{G}_m(\mathbb{R})$ considered as a topological group has two components, the connected component of the identity is $\mathbb{G}_m(\mathbb{R})^{(0)}=\mathbb{R}^\times_{>0}$. Now we enlarge the maximal compact connected subgroup $SO(2) \subset \mathrm{Gl}_2(\mathbb{R})$ to the group $K_\infty = SO(2) \cdot \mathbb{G}_m(\mathbb{R})^{(0)}$. The resulting symmetric space $X = \mathrm{Gl}_2(\mathbb{R})/K_\infty$ is now a union of a upper and a lower half plane: We write $X = \mathbb{H}_+ \cup H_-$.

We choose a positive integer $N > 2$ and consider the congruence subgroup $\Gamma(N) \subset \mathrm{Gl}_2(\mathbb{Q}))$. We modify our symmetric space: This modification may look a little bit artificial at this point, it will be justified in the next chapter and is in fact very natural. (At this point I want to avoid to use the language of adeles.)

We replace the symmetric space by

$$X = (\mathbb{H}_+ \cup \mathbb{H}_-) \times \mathrm{Gl}_2(\mathbb{Z}/N\mathbb{Z}).$$

On this space we have an action of $\Gamma = \mathrm{Gl}_2(\mathbb{Z})$, on the second factor it acts via the homomorphism $\mathrm{Gl}_2(\mathbb{Z}) \to \mathrm{Gl}_2(\mathbb{Z}/N\mathbb{Z})$ by translations from the left. Again we look at the quotient of this space by the action of $\mathrm{Gl}_2(\mathbb{Z})$. This quotient space will have several connected components. The group $\mathrm{Gl}_2(\mathbb{Z})$ contains the group $\mathrm{Sl}_2(\mathbb{Z})$ as a subgroup of index two, because the determinant of an element is ± 1. The element $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ interchanges the upper and the lower half plane and hence we see

$$\mathrm{Gl}_2(\mathbb{Z})\backslash X = \mathrm{Gl}_2(\mathbb{Z})\backslash((\mathbb{H}_+ \cup \mathbb{H}_-) \times \mathrm{Gl}_2(\mathbb{Z}/N\mathbb{Z})) = \mathrm{Sl}_2(\mathbb{Z})\backslash(\mathbb{H}_+ \times \mathrm{Gl}_2(\mathbb{Z}/N\mathbb{Z})),$$

the connected components of $(\mathbb{H}_+ \times \mathrm{Gl}_2(\mathbb{Z}/N\mathbb{Z}))$ are indexed by elements $g \in \mathrm{Gl}_2(\mathbb{Z}/N\mathbb{Z})$. The stabilizer of such a component is the full congruence subgroup

$$\Gamma(N) = \{\gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix} | a, d \equiv 1 \mod N, b, c \equiv 0 \mod N\}$$

this group is torsion free because we assumed $N > 2$.

The image of the natural homomorphism $\mathrm{Sl}_2(\mathbb{Z}) \to \mathrm{Gl}_2(\mathbb{Z}/N\mathbb{Z})$ is the subgroup $\mathrm{Sl}_2(\mathbb{Z}/N\mathbb{Z})$ (strong approximation), therefore the quotient is by this subgroup is $(\mathbb{Z}/N\mathbb{Z})^\times$.

We choose as system of representatives for the determinant the matrices $t_a = \begin{pmatrix} a & 0 \\ 0 & 1 \end{pmatrix}, a \in (\mathbb{Z}/N\mathbb{Z})^\times$. The stabilizer of then we get an isomorphism

$$S_N = \mathrm{Gl}_2(\mathbb{Z})\backslash(\mathbb{H} \times \mathrm{Gl}_2(\mathbb{Z}/N\mathbb{Z})) \xrightarrow{\sim} (\Gamma(N)\backslash\mathbb{H}) \times (\mathbb{Z}/N\mathbb{Z})^\times.$$

To any prime p, which does not divide N we can again attach Hecke operators. Again we can attach Hecke operators

$$T_{p^r} = T\left(\begin{pmatrix} p^r & 0 \\ 0 & 1 \end{pmatrix}, u_{\begin{pmatrix} p^r & 0 \\ 0 & 1 \end{pmatrix}}\right)$$

to the double cosets and using strong approximation we can prove the recursion formulae.

We consider the cohomology groups $H_c^\bullet(S_N, \tilde{\mathcal{M}}_n), H^\bullet(S_N, \tilde{\mathcal{M}}_n)$ and define $H_!^\bullet(S_N, \tilde{\mathcal{M}}_n)$ as before. This is a semi simple module for the cohomology.

The theorem 3 extends to this situation without change. We have a small addendum: If denote by $Z^{(N,\times)} \in \mathbb{Q}^\times$ the subgroup of those numbers which are units at the primes dividing N. We have the homomorphism $r: Z^{(N,\times)} \to (\mathbb{Z}/N\mathbb{Z})^\times$

On each absolutely irreducible component Π_f the Hecke operators $T(z,u_z)$ act by a scalar $\omega(z) \in \mathcal{O}_L$ and the map $z \mapsto \omega(z)$ factors over r and induces a character $\omega(\Pi_f) : (\mathbb{Z}/N\mathbb{Z})^\times \to (\mathcal{O}_L)^\times$. This character is called the central character of Π_f.

The following things will be explained in greater detail in the class

Now we exploit the fact, that the Riemann surface $\Gamma(N)\backslash X$ is in fact the space of complex points of the moduli scheme $M_N \to \operatorname{Spec}(\mathbb{Z}[1/N])$. On this moduli scheme we have the universal elliptic curve with N level structure

$$\begin{array}{c}\mathcal{E}\\ \downarrow \pi\\ M_N\end{array}$$

On $\mathcal{E}$ we have the constant ℓ-adic sheaf $\mathbb{Z}_\ell$. For $i = 0,1,2$ we can consider the ℓ- adic sheaves $R^i\pi_*(\mathbb{Z}_\ell)$ on M_N. We have the spectral sequence

$$H^p(M_N \times \bar{\mathbb{Q}}, R^q\pi_*(\mathbb{Z}_\ell)) \Rightarrow H^n(\mathcal{E} \times \bar{\mathbb{Q}}, \mathbb{Z}_\ell).$$

We can take the fibered product of the universal elliptic curve

$$\mathcal{E}^{(n)} = \mathcal{E} \times_{M_N} \mathcal{E} \times \cdots \times_{M_N} \mathcal{E} \xrightarrow{\pi_N} M_N$$

where n is the number of factors. This gives us a more general spectral sequence

$$H^p(M_N \times \bar{\mathbb{Q}}, R^q\pi_{N,*}(\mathbb{Z}_\ell)) \Rightarrow H^n(\mathcal{E}^{(n)} \times \bar{\mathbb{Q}}, \mathbb{Z}_\ell).$$

The stalk $R^q\pi_{N,*}(\mathbb{Z}_\ell)_y$) of the sheaf $R^q\pi_{N,*}(\mathbb{Z}_\ell)$ in a geometric point y of M_N is the q-th cohomology $H^q(\mathcal{E}_y^{(n)}, \mathbb{Z}_\ell)$ and this can be computed using the Kuenneth formula

$$H^q(\mathcal{E}_y^{(n)}, \mathbb{Z}_\ell) \xrightarrow{\sim} \bigoplus_{a_1,a_2\ldots,a_n} H^{a_1}(\mathcal{E}_y, \mathbb{Z}_\ell) \otimes H^{a_2}(\mathcal{E}_y, \mathbb{Z}_\ell) \cdots \otimes H^{a_n}(\mathcal{E}_y, \mathbb{Z}_\ell),$$

where the $a_i = 0,1,2$ and sum up to q. We have $H^0(\mathcal{E}_y, \mathbb{Z}_\ell) = \mathbb{Z}_\ell(0), H^2(\mathcal{E}_y, \mathbb{Z}_\ell) = \mathbb{Z}_\ell(-1)$ and the most interesting factor is $H^1(\mathcal{E}_y, \mathbb{Z}_\ell)$ which is a free $\mathbb{Z}_\ell$ module af rank 2.

This tells us that the sheaf decomposes into a direct sum according to the type of Kuenneth summands. We also have an action of the symmetric group S_q which is obtained from the permutations of the factors in $\mathcal{E}^{(n)}$ which also permutes the types. We are mainly interested in the case $q = n$ and then we have the special summand where $a_1 = a_2 \cdots = a_n = 1$. This summand is invariant under S_n and contains a summand on which S_n acts by the signature character $\sigma : S_n \to \{\pm 1\}$. This defines a unique subsheaf $R^n\pi_{*,n}(\mathbb{Z}_\ell)(\sigma) \subset R^n\pi_{*,n}(\mathbb{Z}_\ell)$ and hence we get an inclusion

$$H^1(M_N \times \bar{\mathbb{Q}}, R^n\pi_{*,n}(\mathbb{Z}_\ell)(\sigma) \hookrightarrow H^{n+1}(\mathcal{E}^{(n)} \times \bar{\mathbb{Q}}, \mathbb{Z}_\ell)$$

and we can do the same thing for the cohomology with compact supports.

Now I will explain:

A) If we extend the scalars from $\mathbb{Q}$ to $\mathbb{C}$ then then extension of $R^n\pi_{*,n}(\mathbb{Q}_\ell)(\sigma)$ is isomorphic to the restriction of $\mathcal{M}_n \otimes \mathbb{Q}_\ell$ to the etale topology.

B) The Hecke operators T_p for $p \not| N$ are coming from algebraic correspondences $T_p \subset M_N \times M_N$ and induce endomorphisms $T_p : H^1(M_N \otimes \bar{\mathbb{Q}}, R^n\pi_{*,n}(\mathbb{Z}_\ell)(\sigma)) \to H^1(M_N \otimes \bar{\mathbb{Q}}, R^n\pi_{*,n}(\mathbb{Z}_\ell)(\sigma))$ which commute with the action of $\mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ on the cohomology.

C) This tells us that after extension of the scalars of the coefficient system we get

$$H^1(M_N(\mathbb{C}), \mathcal{M}_n \otimes \mathbb{Q}_\ell) \xrightarrow{\sim} H^1(M_N \times \bar{\mathbb{Q}}, R^n\pi_{*,n}(\mathbb{Q}_\ell)(\sigma))$$

and this gives us the structure of a $\mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \times \mathcal{H}_\Gamma$ on $H^1(M_N(\mathbb{C}), \mathcal{M}_n \otimes \mathbb{Q}_\ell)$.

D) The operation of the Galois group on $H^1(M_N(\mathbb{C}), \mathcal{M}_n \otimes \mathbb{Q}_\ell)$ is unramified outside N, therefore we have the conjugacy class Φ_p^{-1} for all $p \not| N$ as endomorphism of $H^1(M_N(\mathbb{C}), \mathcal{M}_n \otimes \mathbb{Q}_\ell)$.

Now we use another fact, which will be explained in Chapter III. We also can define a Hecke algebra $\mathcal{H}_p$ for the primes $p|N$, and hence we get an action of a larger Hecke algebra

$$\mathcal{H}_N^{\text{large}} = {\bigotimes_p}' \mathcal{H}_p$$

and this algebra commutes with the action of the Galois group.

We now apply our theorem 2 to the cohomology $H^1_!(M_N(\mathbb{C}), \mathcal{M}_n \otimes \mathbb{Q}_\ell)$, as a module under this large Hecke algebra. Then the isotypical summands will be invariant under the Galois group.

Theorem 4: *a) The multiplicity of an irreducible representation $\Pi_f \in$ Coh$(M_N(\mathbb{C}), \tilde{\mathcal{M}}_{n,L_\mathfrak{l}})$ is two.*

b) This gives a product decomposition

$$H^1_!(M_N(\mathbb{C}), \mathcal{M}_n \otimes L_\mathfrak{l}) \xrightarrow{\sim} H_{\Pi_f} \otimes W(\Pi_f),,$$

where H_{Π_f} is irreducible of type Π_f and where $W(\Pi_f)$ is a two dimensional Gal$(\bar{\mathbb{Q}}/\mathbb{Q})$ module.

The module $W(\Pi_f)$ is unramified outside N and

$$tr(\Phi_p^{-1}|W(\Pi_f)) = \lambda(\pi_p), \det(\Phi_p^{-1}|W(\Pi_f)) = p^{n+1}\omega(\Pi_f)(p)$$

This theorem is much deeper than the previous ones. The assertion a) follows from the theory of automorphic forms on Gl_2 and b) requires some tools from algebraic geometry. We have to consider the reduction $M_N \times \mathrm{Spec}(\mathbb{F}_p)$ and to look at the reduction of the Hecke operator T_p modulo p. I will resume this discussion in Chap. V.

I want to discuss some applications.

A) To any isotypical component Π_f we can attach an (so called automorphic) L function

$$L(\Pi_f, s) = \prod_p L(\pi_p, s)$$

where for $p \not| N$ we define

$$L(\pi_p, s) = \frac{1}{1 - \lambda(\pi_p)p^{-s} + p^{n+1}\omega(\Pi_f)(p)p^{-2s}}$$

and for $p|N$ we have

$$L(\pi_p, s) = \begin{cases} \frac{1}{1-p^{n+1}\omega(\Pi_f)(p)p^{-s}} & \text{if } \pi_p \text{ is a Steinberg module} \\ 1 & \text{else} \end{cases}$$

This L-function, which is defined as an infinite product is holomorphic for $\Re(s) >> 0$ it can written as the Mellin transform of a holomorphic cusp form F of weight $n+2$ and this implies that

$$\Lambda(\Pi, s) = \frac{\Gamma(s)}{2\pi^s} L(\Pi_f, s)$$

has a holomorphic continuation into the entire complex plane and satisfies a funtional equation

$$\Lambda(\Pi_f, s) = W(\Pi_f)(N(\Pi_f))^{s-1-n/2}\Lambda(\Pi_f, n+2-s)$$

Here $W(\Pi_f)$ is the so called root number, it can be computed from the π_p where $p|N$, its value is ± 1, the number $N(\Pi_f)$ is the conductor of Π_f it is a positive integer, whose prime factors are contained in the set of prime divisors of N.

B) But we also can interpret an isotypic component as a submotive in $H^{n+1}(\mathcal{E}^{(n)} \times \bar{\mathbb{Q}}, \mathbb{Z})$, this is the so called Scholl motive.

If we apply the results of Deligne in Weil II, which have been proved in the winter term 2003/4, we get the estimate

$$|\iota(\lambda(\pi_p))| \leq 2p^{(n+1)/2}$$

for any embedding ι of L into $\mathbb{C}$.

End of probably removed section

2.2.5 The ℓ-adic Galois representation in the first non trivial case

Again we consider the module $\mathcal{M} = \mathcal{M}_{10}[-10]$. We choose a prime ℓ and for some reason let us assume $\ell > 7$. Then we can consider the cohomology groups

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}/\ell^n\tilde{\mathcal{M}})$$

and the projective limit

$$H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_\ell) = \lim_{\leftarrow} H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}/\ell^n\tilde{\mathcal{M}}).$$

Now it is known that the quotient space is the "moduli space" of elliptic curves, this is an imprecise and even incorrect statement, but it contains a lot of truth. What is true is that we can define the moduli stack $S/\operatorname{Spec}(\mathbb{Z})$ of elliptic curves, this is a smooth stack and it has the universal elliptic curve $\mathcal{E} \xrightarrow{\pi} S$ over it.

We can define etale torsion sheaves $(\mathcal{M}/\ell^n\tilde{\mathcal{M}})_{et}$ on this stack and we know that

$$H^1_{et}(S \times_{\operatorname{Spec}(\mathbb{Z})} \bar{\mathbb{Q}}, (\mathcal{M}/\ell^n\tilde{\mathcal{M}})_{et}) \xrightarrow{\sim} H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{10}/\ell^n\tilde{\mathcal{M}}_{10}).$$

On these etale cohomology groups we have an action of the Galois group. Using correspondences we can define Hecke operators T_p for all $p \neq \ell$, they induce endomorphism on the etale cohomology and they commute with the action of the Galois group.

We denote this action of the Galois group as a representation

$$\rho_n : \operatorname{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \operatorname{Gl}(H^1_{et}(S \times_{\operatorname{Spec}(\mathbb{Z})} \bar{\mathbb{Q}}, (\mathcal{M}/\ell^n\tilde{\mathcal{M}})_{et})).$$

This representation is unramified outside ℓ, and this means:

The finite extension $K_\ell^{(n)}/\mathbb{Q}$ for which $\operatorname{Gal}(\bar{\mathbb{Q}}/K_\ell^{(n)})$ is the kernel of ρ_n is unramified outside ℓ.

By transport of structure we have the same projective system of Hecke$\times$Galois modules on the right hand side.

We recall our fundamental exact sequence, the Galois groups acts on the individual terms of this sequence, we get projective systems of Galois-modules and passing to the limit yields

$$\rho_! : \operatorname{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \operatorname{Gl}(H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_\ell))$$

and

$$\rho_\partial : \operatorname{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \operatorname{Gl}(\mathbb{Z}_\ell e_{10}).$$

The field $K_\ell = \bigcup_n K_\ell^{(n)}$ defines the kernel $\operatorname{Gal}(\bar{\mathbb{Q}}/K_\ell)$, the extension $K_\ell/\mathbb{Q}$ is unramified at all primes $p \neq \ell$. If $\mathfrak{p}$ is a prime in $\mathcal{O}_{K_\ell}$ which lies above then the geometric Frobenius $\Phi_\mathfrak{p}$ is the unique element in $\operatorname{Gal}(K_\ell/\mathbb{Q})$ which fixes $\mathfrak{p}$ and induces $x \mapsto x^{-p}$ on the residue field $\mathcal{O}_{K_\ell}/\mathfrak{p}$. This element defines a unique conjugacy class Φ_p in $\operatorname{Gal}(K_\ell/\mathbb{Q})$.

Theorem(Deligne)*For any prime $p \neq \ell$ we have*

$$\rho_\partial(\Phi_p) = p^{11} Id$$

and

$$\det(Id - \rho(\Phi_p)t | H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_\ell)) = 1 - \tau(p)t + p^{11}t^2$$

This is a special case of the general theorem stated in the previous section and it one of the aims of the subject treated in this book to generalize this theorem to larger groups.

We conclude by giving a few applications.

A) The function $z \mapsto \Delta(z)$ is a function on the upper half plane $\mathbb{H} = \{z | \Im(z) > 0\}$ and it satisfies

$$\Delta(\frac{az+b}{cz+d}) = (cz+d)^{12}\Delta(z)$$

and this means that it is a modular form of weight 12. Since it goes to zero if $z = iy \to \infty$ it is even a modular cusp form.

For such a modular cusp form we can define the Hecke L-function

$$L(\Delta,s)=\int_0^\infty \Delta(iy)y^s\frac{dy}{y}=\frac{\Gamma(s)}{(2\pi)^s}\sum_{n=1}^\infty\frac{\tau(n)}{n^s}=\frac{\Gamma(s)}{(2\pi)^s}\prod_p\frac{1}{1-\tau(p)p^{-s}+p^{11-2s}}$$

the product expansion has been discovered by Ramanujan and has been proved by Mordell and Hecke.

Now it is in any textbook on modular forms that the transformation rule

$$\Delta(-\frac{1}{z})=z^{12}\Delta(z)$$

implies that $L(\Delta,s)$ defines a holomorphic function in the entire s plane and satisfies the functional equation

$$L(\Delta,s)=(-1)^{12/2}L(\Delta,12-s)=L(\Delta,12-s).$$

This function $L(\Delta,s)$ is the prototype of an automorphic L-function. The above theorem shows that it is equal to a "motivic" L-function. We gave some vague explanations of what this possibly means: We can interpret the projective system $(\mathcal{M}/\ell^n\tilde{\mathcal{M}})_{et}$ as the $\ell-$adic realization of a motive:

$$\mathcal{M}=\mathrm{Sym}^{10}(R^1(\pi:\mathcal{E}\to S))$$

(All this is a translation of Deligne‘s reasoning into a more sophisticated language.)

It is a general hope that "motivic" L-functions $L(M,s)$ have nice properties as functions in the variable s (meromorphicity, control of the poles, functional equation). So far the only cases, in which one could prove such nice properties are cases where one could identify the "motivic" L-function to an automorphic L function. The greatest success of this strategy is Wiles‘ proof of the Shimura-Taniyama-Weil conjecture, but also the Riemann ζ-function is a motivic $L-$function and Riemann‘s proof of the functional equation follows exactly this strategy.

B) But we also have a flow of information in the opposite direction. In 1973 Deligne proved the Weil conjectures which in this case say that the two roots of the quadratic equation

$$x^2-\tau(p)x+p^{11}=0$$

have absolute value $p^{11/2}$, i.e. they have the same absolute value. This implies the famous Ramanujan- conjecture

$$\tau(p)\leq 2p^{11/2}$$

and for more than 50 years this has been a brain-teaser for mathematicians working in the field of modular forms.

C) We consider the Galois representation

$$\rho:\ \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})\to \mathrm{Gl}(H^1(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}\otimes\mathbb{Z}_\ell))$$

and and its sub and quotient representations

$$\rho_!:\ \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})\to \mathrm{Gl}(H^1_!(\Gamma\backslash\mathbb{H},\tilde{\mathcal{M}}\otimes\mathbb{Z}_\ell)),\rho_\partial:\ \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})\to \mathrm{Gl}(\mathbb{Z}_\ell e_{10}).$$

The representation ρ_∂ is the $\ell-$ adic realization of the Tate-motive $\mathbb{Z}(-11)$ (For a slightly more precise explanation I refer to MixMot.pdf on my homepage). On $\mathbb{Z}_\ell(-1) = H^2(\mathbb{P}^1\times\bar{\mathbb{Q}}, \mathbb{Z}_\ell)$ the Galois group acts by the Tate-character

$$\mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \mathrm{Gal}(\mathbb{Q}(\zeta_{\ell^\infty})/\mathbb{Q}) \xrightarrow{\alpha} \mathbb{Z}_\ell^\times$$

where $\mathbb{Q}(\zeta_{\ell^\infty})$ is the cyclotomic field of all ℓ^n-th roots of unity ($n \to \infty$). We identify $\mathrm{Gal}(\mathbb{Q}(\zeta_{\ell^\infty})/\mathbb{Q}) = \mathbb{Z}_\ell^\times$, the identification is given by the map $x \mapsto (\zeta \mapsto \zeta^x)$ and then $\alpha(x) = x^{-1}$. Hence the first assertion in Delignes theorem simply says:

$$\rho_\partial = \alpha^{11}.$$

We say a few words concerning

$$\rho_! : \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \mathrm{Gl}(H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_\ell)).$$

It is easy to see that the cup product provides a non degenerate alternating pairing

$$< , >: H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_\ell) \times H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_\ell) \to \mathbb{Z}_\ell(-11)$$

and clearly for any $\sigma \in \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ we must have

$$< \rho(\sigma)u, \rho(\sigma)v >= \alpha^{11}(\sigma) < u, v > .$$

This means we have $\det(\rho(\sigma)) = \alpha^{11}(\sigma)$ and we can ask what is the image of $\mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ in $\mathrm{Gl}(H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_\ell) = \mathrm{Gl}_2(\mathbb{Z}_\ell)$. We ask a seemingly simpler question and we want to understand the image of

$$\rho_{!,\mod \ell}\ \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \mathrm{Gl}(H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{F}_\ell) = \mathrm{Gl}_2(\mathbb{F}_\ell).$$

This question is discussed in the paper " On ℓ-adic representations and congruences for coefficients of modular forms," Springer lecture Notes 350, Modular Functions of one Variable III by H.P.F. Swinnerton-Dyer.

Here we can say that the image of this homomorphism composed with the determinant will be $(\mathbb{F}_\ell^\times)^{11} \subset \mathbb{F}_\ell^\times$. It is shown in the above paper that for $\ell \neq 2, 3, 5, 7, 23, 691$ the image of the Galois group will simply be as large as possible, namely it will be the inverse image of $(\mathbb{F}_\ell^\times)^{11}$.

We can apply the Manin-Drinfeld principle and conclude that after tensorization by $\mathbb{Q}_\ell$ the representation $\rho \otimes \mathbb{Q}_\ell$ splits

$$\rho \otimes \mathbb{Q}_\ell = \rho_1 \otimes \mathbb{Q}_\ell \oplus \mathbb{Q}_\ell e_{10}(-11).$$

In section 2.2.3 we have seen that we have such a splitting also for the integral cohomology, i.e. for the module $H^1(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}} \otimes \mathbb{Z}_\ell)$ provided ℓ is not one of the small primes, which have been inverted and $\ell \neq 691$.

But if $\ell = 691$ then we have seen in 2.2.3 that we have a homomorphism

$$j : \mathbb{Z}/(691)(-11) \hookrightarrow H^1_!(\Gamma\backslash\mathbb{H}, \tilde{\mathcal{M}}_{\mathbb{Z}/(691)}),$$

this is a homomorphism of Galois-modules. This means that the representation of the of the Galois group modulo $\ell = 691$ is of the form

$$\rho_{!,\quad \mathrm{mod}\ 691}: \ \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \begin{pmatrix} * & * \\ 0 & * \end{pmatrix}$$

$$\rho_{!,\quad \mathrm{mod}\ 691}(\sigma) \mapsto \begin{pmatrix} \alpha(\sigma)^{11} & u(\sigma) \\ 0 & 1 \end{pmatrix}$$

The field $K^{(1)}_{691}$ contains the $691-$ th roots of unity and is an unramified extension of degree 691, in a sense this extension is now obtained by an explicit construction.

Chapter 6

Cohomology in the adelic language

6.1 The spaces

6.1.1 The (generalized) symmetric spaces

Our basic datum is a connected reductive group $G/\mathbb{Q}$. Let $G^{(1)}/\mathbb{Q}$ be its derived group and let $C/\mathbb{Q}$ its centre. Then $G^{(1)}/\mathbb{Q}$ is semi simple and $C/\mathbb{Q}$ is a torus. The multiplication provides a canonical map

$$m : C \times G^{(1)} \to G \tag{6.1}$$

it is is an isogeny, this means that the kernel $\mu_C = C \cap G^{(1)}$ of this map is a finite group scheme of multiplicative type. A finite group scheme of multiplicative type is simply an abelian group together with an action of the Galois group $\mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ on it. If we have such an isogeny as in (6.1) we write $G = C \cdot G^{(1)}$.

Let $S/\mathbb{Q}$ be the maximal $\mathbb{Q}$ -split torus in $C/\mathbb{Q}$. Up to isogeny we have $C = C_1 \cdot S$ where C_1 is the maximal anisotropic subtorus of $C/\mathbb{Q}$. We also introduce the group $G_1 = G^{(1)} \cdot C_1$. We have an exact sequence

$$1 \to G^{(1)} \to G \xrightarrow{d_C} C' \to 1,$$

the quotient C' is a torus and the restricted map $d_C : C \to C'$ is an isogeny.

If $\tilde{G}^{(1)}/\mathbb{Q}$ is the simply connected covering of $G^{(1)}$, then we get an isogeny

$$m_1 : \tilde{G} = \tilde{G}^{(1)} \times C_1 \times S \to G \tag{6.2}$$

Let $\mathfrak{g}, \mathfrak{g}^{(1)}, \mathfrak{c}, \mathfrak{c}_1, \mathfrak{z}$ be the Lie algebras of $G/\mathbb{Q}, G^{(1)}/\mathbb{Q}, C/\mathbb{Q}, C_1/\mathbb{Q}, S/\mathbb{Q}$, then the differential of m_1 induces an isomorphism

$$D_{m_1} : \mathfrak{g} \to \mathfrak{g}^{(1)} \oplus \mathfrak{c}_1 \oplus \mathfrak{z} \tag{6.3}$$

On $\mathfrak{g}$ we have the Killing form $B : \mathfrak{g} \times \mathfrak{g} \to \mathbb{Q}$ be the Killing form, it is defined by the rule

$$(T_1, T_2) \mapsto \mathrm{trace}(\mathrm{ad}(T_1) \circ \mathrm{ad}(T_2)) \tag{6.4}$$

(See [chap2] 1.2.2) The Killing form is actually a bilinear form on $\mathfrak{g}^{(1)} = \mathfrak{g}/(\mathfrak{c}_1 \oplus \mathfrak{z})$ and the restriction $B : \mathfrak{g}^{(1)} \times \mathfrak{g}^{(1)} \to \mathbb{Q}$ is nondegenerate (see chap2 and chap4).

An automorphism $\Theta : \tilde{G}^{(1)} \times_{\mathbb{Q}} \mathbb{R} \to \tilde{G}^{(1)} \times_{\mathbb{Q}} \mathbb{R}$ is called a Cartan involution if $\Theta^2 = \mathrm{Id}$ and if the bilinear form

$$B_\Theta(T_1, T_2) = B(T_1, \Theta(T_2)) \tag{6.5}$$

on $\mathfrak{g} \otimes \mathbb{R}$ is negative definite.

If Θ is a Cartan involution then it induces an automorphism -also called Θ- on the Lie algebra $\mathfrak{g}_{\mathbb{R}} = \mathfrak{g} \otimes \mathbb{R}$ and decomposes it into a $+$ and a $-$ eigenspace

$$\mathfrak{g}_{\mathbb{R}} = \mathfrak{k} \oplus \mathfrak{p} \tag{6.6}$$

and then clearly the $+$ eigenspace $\mathfrak{k}$ is a Lie subalgebra and $[\mathfrak{p}, \mathfrak{p}] \subset \mathfrak{k}$. The Killing form is negative definite on $\mathfrak{k}$ and positive definite on $\mathfrak{p}$. This explains the above assertion on B_Θ.

The topological group of real points $\tilde{G}^{(1)}(\mathbb{R})$ is connected (see ref?). Then we have the classical theorem

Theorem 6.1.1. *The fixed group $K_\infty^{(1)} = \tilde{G}^{(1)}(\mathbb{R})^\Theta$ is a maximal compact subgroup and it is also connected. The Cartan involutions are conjugate under the action of $\tilde{G}^{(1)}(\mathbb{R})$, and therefore the maximal compact subgroups of $\tilde{G}^{(1)}(\mathbb{R})$ are conjugate.*

We introduce the space $\tilde{X}^{(1)}$ of Cartan involutions on $\tilde{G}^{(1)} \times_{\mathbb{Q}} \mathbb{R}$, it is a homogenous space under the action of $\tilde{G}^{(1)}(\mathbb{R})$ by conjugation and if we choose a Θ or $K_\infty^{(1)}$ then

$$\tilde{X}^{(1)} = \tilde{G}^{(1)}(\mathbb{R})/K_\infty^{(1)} \tag{6.7}$$

This is the symmetric space attached to $\tilde{G}^{(1)} \times_{\mathbb{Q}} \mathbb{R}$.

Proposition 6.1.1. *The symmetric space $\tilde{X}^{(1)} = \tilde{G}^{(1)}(\mathbb{R})/K_\infty^{(1)}$ is diffeomorphic to $\mathbb{R}^d$, where $d = \dim \mathfrak{p}$, it carries a Riemannian metric which is $\tilde{G}^{(1)}(\mathbb{R})$ invariant.*

We have to be aware that it may happen that Θ is the identity. Then $\tilde{G}^{(1)}(\mathbb{R}) = K_\infty^{(1)}$ and our symmetric space is a point.

We extend Θ to an involution on $\tilde{G} \times \mathbb{R}$ it will be simply the identity on the other two factors. Then it also induces an involution, again called Θ on $G \times \mathbb{R}$.

We return to our reductive group $G/\mathbb{Q}$. We compare it to $\tilde{G}$ via the homomorphism m_1 in (6.2). Let K_∞^C be the connected component of the identity of the maximal compact subgroup in $C_1(\mathbb{R})$ and let $Z'(\mathbb{R})^0$ be the connected component of the identity of the group of real points a subtorus $Z' \subset S$. Then we put

$$K_\infty = m_1(K_\infty^{(1)} \times K_\infty^C \times Z'(\mathbb{R})^0)$$

This group K_∞ is connected and if we divide by $Z'(\mathbb{R})^0$ it is compact, more precisely we can say that $K_\infty/Z'(\mathbb{R})^0$ is the connected component of a maximal compact subgroup in $G(\mathbb{R})/Z'(\mathbb{R})^0$. The choice of the subtorus Z' is arbitrary and in a certain sense irrelevant. We could choose $Z' = Z$ then we call K_∞ *saturated* , this choice is very convenient but it certain situations it is better to make a different choice, for instance we may choose $Z' = 1$.

To such a pair (G, K_∞) we attach the *(generalized) symmetric space*

$$X = G(\mathbb{R})/K_\infty.$$

Here are a few comments concerning the structure of this space. (see also Chap II. 1.3) We observe that by construction K_∞ is connected, hence we have that $K_\infty \subset G(\mathbb{R})^0$. So if as usual $\pi_0(G(\mathbb{R}))$ denotes the set of connected components, then we see that

$$\pi_0(X) = \pi_0(G(\mathbb{R})).$$

The connected component of the identity of $\tilde{G}(\mathbb{R})$ maps under m_1 to the connected component of he identity of $G(\mathbb{R})$, i.e.

$$\tilde{G}(\mathbb{R}) = \tilde{G}^{(1)}(\mathbb{R}) \times C_1(\mathbb{R})^0 \times S(\mathbb{R})^0 \to G(\mathbb{R})^0$$

and if we divide by $K_\infty^{(1)} \times K_\infty^C \times Z'(\mathbb{R})^0$, resp. K_∞ we get a diffeomorphism with the connected component corresponding to the identity

$$\tilde{G}^{(1)}(\mathbb{R})/K_\infty^{(1)} \times C_1(\mathbb{R})^0/K_\infty^C \times S(\mathbb{R})^0/Z'(\mathbb{R}) \xrightarrow{\sim} X_1 \subset X.$$

We want to describe the other connected components of X. It is well known that we can find a maximal split torus $\tilde{S}_1 \subset \tilde{G}^{(1)} \times \mathbb{R}$ which is invariant under our given Cartan involution Θ. The homomorphism m_1 maps $\tilde{G}^{(1)}(\mathbb{R}) \to G^{(1)}(\mathbb{R})$. The fixed group $G^{(1)}(\mathbb{R})^\Theta$ is a compact subgroup whose connected component of the identity is the image of $K_\infty^{(1)}$ under m_1. Our torus $\tilde{S}_1$ sits as the first component in the maximal split torus

$$\tilde{S}_2 = \tilde{S}_1 \times C_1^{\text{split}} \times S$$

Then it is clear that Θ induces the involution $t \mapsto t^{-1}$ on $\tilde{S}_1$. Let S_2 be the image of $\tilde{S}_2$ under m_1. We have the following proposition

Proposition 6.1.2. *a)The group of 2-division points $S_2[2]$ normalizes K_∞.*

b) We have an exact sequence

$$\to \tilde{S}_2[2] \to S_2[2] \xrightarrow{r} \pi_0(G(\mathbb{R})) \to 0$$

c) If K_∞^0 is the image of $K_\infty^{(1)} \times K_\infty^C$ then $K_\infty^0 \cdot S_2[2]$ is a maximal compact subgroup of $G(\mathbb{R})$.

Proof. Rather obvious, the surjectivity of r requires an argument in Galois cohomology. (Details later) □

Now we can write down all the connected components. We choose a system Ξ of representatives for $S_2[2]/\tilde{S}_2[2]$ and for any $\xi \in \Xi$ we get a diffeomorphism

$$\begin{gathered}\tilde{G}^{(1)}(\mathbb{R})/K_\infty^{(1)} \times C_1(\mathbb{R})^0/K_\infty^C \times S(\mathbb{R})^0/Z'(\mathbb{R}) \to X_\xi \subset X \\ g \mapsto g\xi\end{gathered} \tag{6.8}$$

We may formulate this differently

Proposition 6.1.3. *The multiplication from the left by $S_2[2]$ on $G(\mathbb{R})$ induces an action of $S_2[2]/\tilde{S}_2[2]$ on X and this action is simple transitive on the set of connected components.*

Let $x_0 = K_\infty \in X$. For any other point $x \in X$ we find an element $g \in X$ which translates x_0 to x. Then the derivative of the translation provides an isomorphism between the tangent spaces

$$D_g : T_{x_0} = \mathfrak{p} \xrightarrow{\sim} T_x.$$

This isomorphism depends of course on the choice of g. (This will play a role in section (8.1)). But we apply this to the highest exterior power and get an isomorphism

$$D_g : \Lambda^d(\mathfrak{p}) \xrightarrow{\sim} \Lambda^d(T_x)$$

which does not depend on the choice of g because the connected group K_∞ acts trivially on $\Lambda^d(\mathfrak{p})$. Hence we can say that we can find a *consistent* orientation on X : We chose a generator in $\Lambda^d(\mathfrak{p})$ the D_g yields a generator in $\Lambda^d(T_x)$.

If our reductive group is an anisotropic torus $T/\mathbb{Q}$, then we have for the connected component of the identity

$$T(\mathbb{R})^{(0)} \xrightarrow{\sim} (\mathbb{R}^\times_{>0})^a \times (S^1)^b.$$

Then our maximal compact subgroup K^T_∞ is simply the product of the circles and

$$X_T = T(\mathbb{R})/K^T_\infty$$

is nothing else than as disjoint union of copies of $\mathbb{R}^a$. The situation is similar for a split torus but then we have the freedom, to divide out the connected component of a subtorus.

As a standard example we can take $G/\mathbb{Q} = \mathrm{Gl}_2/\mathbb{Q}$, then the connected component of the real points of the centre is $\mathbb{R}^\times_{>0}$ and in this case we can take $K_\infty = SO(2) \cdot \mathbb{R}^\times_{>0} \subset \mathrm{Gl}_2(\mathbb{R}))$. In this case the symmetric space is the union of an upper and a lower half plane. It we choose for our split torus $S_1/\mathbb{R}$ the standard diagonal torus, then $S_1[2]$ is the group of diagonal matrices with entries ± 1 and this normalizes K_∞.

6.1.2 The locally symmetric spaces

Let $\mathbb{A}$ be the ring of adeles, we decompose it into its finite and its infinite part: $\mathbb{A} = \mathbb{R} \times \mathbb{A}_f$. We have the group of adeles $G(\mathbb{A}) = G(\mathbb{R}) \times G(\mathbb{A}_f)$. We denote elements in the adele group by underlined letters $\underline{g}, \underline{h} \ldots$ and so on. If we decompose an element $\underline{g}$ into its finite and its infinite part then we denote this by $g_\infty \times \underline{g}_f$. Let K_f be a (variable) open compact subgroup of $G(\mathbb{A}_f)$. We always assume that this group is a product of local groups $K_f = \prod_p K_p$.

To get such subgroups we choose an integral structure (explain at some other place) $\mathbb{G}/\operatorname{Spec}(\mathbb{Z})$. Then we know that we have $K_p = \mathbb{G}(\mathbb{Z}_p)$ for almost all p. Furthermore we know that $\mathbb{G}\times \operatorname{Spec}(\mathbb{Z}_p)/\operatorname{Spec}(\mathbb{Z}_p)$ is a reductive group scheme for almost all primes p.

If $\mathbb{G}/\operatorname{Spec}(\mathbb{Z})$ and K_f are given, then we select a finite set Σ of finite primes which contains the primes p where $\mathbb{G}/\mathbb{Z}_p$ is not reductive and those where K_p is not equal to $\mathbb{G}(\mathbb{Z}_p)$. This set Σ will be called the set of *ramified* primes.

The general agreement will be that we use letters $\mathcal{G}, \mathcal{T}, \mathcal{U}, \ldots$ for group schemes over the integers, or over $\mathbb{Z}_p$ and then their general fiber will be $G, T, U, \ldots$.

Readers who are not so familiar with this language may think of the simple example where $G/\mathbb{Q} = GSp_n/\mathbb{Q}$ is the group of symplectic similitudes on $V = \mathbb{Q}^{2n} = \mathbb{Q}e_1 \oplus \cdots \oplus \mathbb{Q}e_n \oplus \mathbb{Q}f_1 \oplus \cdots \oplus \mathbb{Q}f_n$ with the standard symplectic form which is given by $< e_i, f_i >= 1$ for all i and where all other products zero. The vector space contains the lattice $L = \mathbb{Z}^{2n} = \mathbb{Z}e_1 \oplus \cdots \oplus \mathbb{Z}e_n \oplus \mathbb{Z}f_1 \oplus \cdots \oplus \mathbb{Z}f_n$. This lattice defines a unique integral structure $\mathbb{G}/\mathbb{Z}$ on $G/\mathbb{Q}$ for which $\mathbb{G}(\mathbb{Z}_p) = \{g \in G(\mathbb{Q}_p) | g(L \otimes \mathbb{Z}_p) = (L \otimes \mathbb{Z}_p)\}$. In this case the group scheme is reductive over $\mathrm{Spec}(\mathbb{Z})$. This integral structure gives us a privileged choice of an open maximal compact subgroup: Within the ring $\mathbb{A}_f$ of finite adeles we have the ring $\hat{\mathbb{Z}} = \lim\limits_{\leftarrow} \mathbb{Z}/m\mathbb{Z}$ of integral finite adeles and we can consider $K_f^0 = \mathbb{G}(\hat{\mathbb{Z}}) = \prod_p \mathbb{G}(\mathbb{Z}_p)$. This is a very specific choice. In this case the set $\Sigma = \emptyset$, we say that $K_f = K_f^0$ is unramified.

Starting from there we can define new subgroups K_f by imposing some congruence conditions at a finite set Σ of primes. These congruence conditions then define congruence subgroups $K_p \subset K_p^0$. This set Σ of places where we impose congruence condition will then be the set of ramified primes.(See the example further down.) Then we define the level subgroup

$$K_f = \prod_{p \in \Sigma} K_p \times \prod_{p \notin \Sigma} \mathbb{G}(\mathbb{Z}_p). \tag{6.9}$$

The space $(G(\mathbb{R})/K_\infty) \times (G(\mathbb{A}_f)/K_f)$ can be seen as a product of the symmetric space and an infinite discrete set, on this space $G(\mathbb{Q})$ acts properly discontinuously (see below) and the quotients

$$\mathcal{S}^G_{K_f} = G(\mathbb{Q}) \setminus (G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f)$$

are the locally symmetric spaces whose topological properties we want to study. We denote by

$$\pi : G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f \to \mathcal{S}^G_{K_f} = G(\mathbb{Q}) \setminus (G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f),$$

the projection map.

To get an idea of how this space looks like we consider the action of $G(\mathbb{Q})$ on the discrete space $G(\mathbb{A}_f)/K_f$. It follows from classical finiteness results that this quotient is finite, let us pick representatives $\{\underline{g}_f^{(i)}\}_{i=1..m}$. We look at the stabilizer of the coset $\underline{g}_f^{(i)} K_f/K_f$ in $G(\mathbb{Q})$. This stabilizer is obviously equal to $\Gamma^{\underline{g}_f^{(i)}} = G(\mathbb{Q}) \cap \underline{g}_f^{(i)} K_f (\underline{g}_f^{(i)})^{-1}$ which is an arithmetic subgroup of $G(\mathbb{Q})$. This subgroup acts properly discontinuously on X (See Chap. II, 1.6).

Now we call the level subgroup K_f neat, if all the subgroups $\Gamma^{\underline{g}_f^{(i)}}$ are torsion free. It is not hard to see, that for any choice of K_f we can pass to a subgroup of finite index K'_f, which is neat. Then we have

1.2.1 *For any subgroup K_f the space $\mathcal{S}^G_{K_f}$ is a finite union of quotient spaces $\Gamma^{\underline{g}_f^{(i)}} \setminus X$ where $X = G(\mathbb{R})/K_\infty$ and the $\Gamma_i = \Gamma^{\underline{g}_f^{(i)}}$ are varying arithmetic* *congruence subgroups. If K_f is neat, these spaces are locally symmetric spaces. If K_f is not neat then we may pass to a neat subgroup K'_f which is even normal in K_f: We get a covering $\mathcal{S}^G_{K'_f} \to \mathcal{S}^G_{K_f}$ which induces coverings $\Gamma'_j\backslash X \to \Gamma_i\backslash X$, where the Γ'_j are torsion free and normal in Γ_i. So we see that in general the quotients are orbifold locally symmetric spaces. For any point $y \in \mathcal{S}^G_{K_f}$ we can find a neighborhood V_y such that $\pi^{-1}(V_y)$ is the disjoint union of connected components $W_{\underline{x}}, \underline{x} = (x_\infty, \underline{g}_f) \in \pi^{-1}(y)$, and $V_y = \Gamma_{x_\infty}\backslash W_{\underline{g}_f}$, where Γ_{x_∞} is the stabilizer of x_∞ intersected with $\Gamma^{\underline{g}_f}$.*

We will consider the special case where $G/\mathbb{Q}$ is the generic fibre of a split reductive scheme $\mathcal{G}/\mathbb{Z}$. In that case we can choose $K_f = \prod_p \mathcal{G}(\mathbb{Z}_p)$, this is then a maximal compact subgroup in $G(\mathbb{A}_f)$. Then K_f is unramified we will also say that the space $\mathcal{S}^G_{K_f}$ is unramified. If in addition the derived group $G^{(1)}/\mathbb{Q}$ is simply connected, then it is not difficult to see, that $G(\mathbb{Q})$ acts transitively on $G(\mathbb{A}_f)/K_f$ and hence we get

$$\mathcal{S}^G_{K_f} \xrightarrow{\sim} \mathcal{G}(\mathbb{Z})\backslash X.$$

The homomorphism $\mathbb{G}(\mathbb{Z}) \to \pi_0(C'(\mathbb{R}))$ is surjective we can conclude that $\mathbb{G}(\mathbb{Z})$ acts transitively on $\pi_0(X)$ and if Γ_0 is the stabilizer of a connected component X^0 of X then we find

$$\mathcal{S}^G_{K_f} \xrightarrow{\sim} \Gamma_0\backslash X^0$$

especially we see that the quotient is connected. We discuss an example.

We start from the group $G/\operatorname{Spec}(\mathbb{Z}) = \mathrm{Gl}_n/\operatorname{Spec}(\mathbb{Z})$ then we may choose $K_\infty = \mathrm{SO}(n) \times \mathbb{R}^\times_{>0} \subset \mathrm{Gl}_n(\mathbb{R})$. and $X = \mathrm{Gl}_n(\mathbb{R})/K_\infty$ is the disjoint union of two copies of the space X of positive definite symmetric $(n \times n)$ matrices up to homothetie by a positive scalar (or what amounts to the same with determinant one). If we choose K_f as above then we find

$$\mathcal{S}^G_{K_f} = \mathrm{Sl}_n(\mathbb{Z})\backslash X.$$

We have another special case. Let us assume that $G/\mathbb{Q}$ is semi simple and simply connected. The group $G \times \mathbb{R}$ is a product of simple groups over $\mathbb{R}$ and we assume in addition that no no simple factor is compact. Then we have the strong approximation theorem (Kneser and Platonov) which says that for any choice of K_f the map from $G(\mathbb{Q})$ to $G(\mathbb{A}_f)/K_f$ is surjective, i.e. any $\underline{g}_f \in G(\mathbb{A}_f)$ can be written as $\underline{g}_f = a\underline{k}_f, a \in G(\mathbb{Q}), \underline{k}_f \in K_f$. This clearly implies that then

$$\mathcal{S}^G_{K_f} = \Gamma\backslash G(\mathbb{R})/K_\infty \tag{6.10}$$

where $\Gamma = K_f \cap G(\mathbb{Q})$.

There is a contrasting case, this is the case when $G/\mathbb{Q}$ is still semi simple and simply connected, but where $G(\mathbb{R})$ is compact. In this case our symmetric space X is simply a point $*$ and

$$\mathcal{S}^G_{K_f} = G(\mathbb{Q})\backslash(* \times G(\mathbb{A}_f)/K_f).$$

In this case the topological space is just a discrete set of points. So it looks as if this is an entirely uninteresting and trivial case, but this is not so. To determine the finite set and the stabilizers is a highly non trivial task. Later we will construct sheaves and discuss the action of the Hecke algebra on the cohomology of these sheaves. Then it turns out that this case is as difficult as the case where $\Gamma\backslash X$ becomes an honest space.

In the choice of our group K_∞ a subtorus $Z' \subset S$ enters. The choice of this subtorus has very little influence on the structure of our locally symmetric space $\mathcal{S}^G_{K_f}$. Remember that the isogeny m in (6.1) induces an isogeny $C \to C'$ and this isogeny yields an isogeny from S to the maximal split subtorus $S' \subset C'$. This homomorphism induces an isomorphism $S(\mathbb{R})^0 \to S'(\mathbb{R})^0$. If $G_1(\mathbb{R})$ is the inverse image of the the group of 2-division points $S'[2]$ then we get from this isomorphism that $G(\mathbb{R}) = G_1(\mathbb{R}) \times S(\mathbb{R})^0$. If we now consider the two spaces $\mathcal{S}^G_{K_f}$ and $(\mathcal{S}^G_{K_f})^\dagger$, the first one defined with an arbitrary torus Z' the second one with $Z' = S$ then the arguments above imply that

$$\mathcal{S}^G_{K_f} = (\mathcal{S}^G_{K_f})^\dagger \times (S(\mathbb{R})^0/Z'(\mathbb{R})^0) \tag{6.11}$$

the second factor on the right hand side is isomorphic to $\mathbb{R}^b$ and since we are interested in the cohomology group of this space, it is irrelevant.

In certain situations we encounter cases where it is natural to choose a subgroup K_∞ which is slightly larger and not connected. If this is the case we denote the connected component $K^{(1)}_\infty$ and we get two locally symmetric spaces and a finite map

$$G(\mathbb{Q}) \setminus \left(G(\mathbb{R})/K^{(1)}_\infty \times G(\mathbb{A}_f)/K_f\right) \to G(\mathbb{Q}) \setminus (G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f) \tag{6.12}$$

This map is a covering if K_f is neat and the space on the right is a quotient of the space on the left by an action of the finite elementary abelian [2]-group $K_\infty/K^{(1)}_\infty$.

In accordance with the terminology in number theory we call the space $\mathcal{S}^G_{K_f}$ *narrow* if $K^{(1)}_\infty = K_\infty$ and in general we call the space on the left the *narrow cover* of $G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f$.

6.1.3 The group of connected components, the structure of $\pi_0(\mathcal{S}^G_{K_f})$.

If we keep our assumptions that $G/\mathbb{Q}$ is split and $G^{(1)}/\mathbb{Q}$ simply connected. Then it is straightforward to show that under our assumptions we have a bijection

$$\pi_0(\mathcal{S}^G_{K_f}) \xrightarrow{\sim} \pi_0(\mathcal{S}^{C'}_{K^{C'}_\infty \times K^{C'}_f}) \tag{6.13}$$

We have seen in the previous section that we can choose a consistent orientation on $X = G(\mathbb{R})/K_\infty$ provided K_∞ is narrow. Then it clear this induces also a consistent orientation on $\mathcal{S}^G_{K_f}$.

6.1.4 The Borel-Serre compactification

In general the space $\mathcal{S}^G_{K_f}$ is not compact. Recall that in the definition of this quotient the choice of a subtorus $Z'/\mathbb{Q}$ of $S/\mathbb{Q}$ enters. This If $Z' \neq S$ then the quotient will never be compact. But this kind of non compactness is "uninteresting". In the following we assume that $Z' = S$.

In this case we have the criterion of Borel - Harish-Chandra which says

The quotient space $\mathcal{S}^G_{K_f}$ is compact if and only if the group $G/\mathbb{Q}$ has no proper parabolic subgroup over $\mathbb{Q}$.

If we have a non trivial parabolic subgroup $P/\mathbb{Q}$ then we add a boundary part $\partial_P \mathcal{S}^G_{K_f}$ to $\mathcal{S}^G_{K_f}$ it will depend only the $G(\mathbb{Q})$-conjugacy class of P. We will describe this boundary piece later. We define the Borel-Serre boundary

$$\partial(\mathcal{S}^G_{K_f}) = \bigcup_P \partial_P \mathcal{S}^G_{K_f},$$

where P runs over the set of $G(\mathbb{Q})$ conjugacy classes of parabolic subgroups. We will put a topology on this space and if $Q \subset P$ then $\partial_Q \mathcal{S}^G_{K_f}$ will be in the closure of $\partial_P \mathcal{S}^G_{K_f}$. Then

$$\bar{\mathcal{S}^G_{K_f}} = \mathcal{S}^G_{K_f} \cup \partial(\mathcal{S}^G_{K_f})$$

will be a compact Hausdorff-space.

We describe the construction of this compactification in more detail. In chap4.pdf 2.7.1 we studied the group $\mathrm{Hom}(P, \mathbb{G}_m)$ and have seen that

$$\mathrm{Hom}(P, \mathbb{G}_m) \otimes \mathbb{Q} = \mathrm{Hom}(S_P, \mathbb{G}_m) \otimes \mathbb{Q}.$$

For any character $\gamma \in \mathrm{Hom}(P, \mathbb{G}_m)$ we get a homomorphism $\gamma_A : P(\mathbb{A}) \to \mathbb{G}_m(\mathbb{A}) = I_{\mathbb{Q}}$, the group of ideles. We have the idele norm $|\ | : \underline{x} \mapsto |\underline{x}|$ from the idele group to $\mathbb{R}^\times_{>0}$ and then we get by composing

$$|\gamma| : P(\mathbb{A}) \to \mathbb{R}^\times_{>0}.$$

It is obvious that we can extend this definition to characters $\gamma \in \mathrm{Hom}(P, \mathbb{G}_m) \otimes \mathbb{Q}$, for such a γ we find a positive non zero integer m such that $m\gamma \in \mathrm{Hom}(P, \mathbb{G}_m)$ and then we define

$$|\gamma| = (|m\gamma|)^{\frac{1}{m}}$$

Later we will even extend this to a homomorphism $\mathrm{Hom}(P, \mathbb{G}_m) \otimes \mathbb{C} \to \mathrm{Hom}(P(\mathbb{A}), \mathbb{C}^\times)$ by the rule $\boxed{\text{XtimesC}}$

$$\gamma \otimes z \mapsto |\gamma|^z \tag{6.14}$$

If we have a parabolic subgroup $P/\mathbb{Q}$ and a point $(x, \underline{g}_f) \in X \times G(\mathbb{A}_f)/K_f$ then we attach to it a (strictly positive) number

$$p(P, (x, \underline{g}_f)) = \mathrm{vol}_{d_x u}(U(\mathbb{Q}) \cap \underline{g}_f K_f \underline{g}_f^{-1} \backslash U(\mathbb{R})). \tag{6.15}$$

This needs explanation. The group $U(\mathbb{Q}) \cap \underline{g}_f K_f \underline{g}_f^{-1} = \Gamma_{U, \underline{g}_f}$ is a cocompact discrete lattice in $U(\mathbb{R})$, we can describe it as the group of elements $\gamma \in U(\mathbb{Q})$

which fix $\underline{g}_f K_f$, so it can be viewed as a lattice of integral elements where integrality is determined by $\underline{g}_f$. The point x defines a positive definite bilinear form B_{Θ_x} on the Lie algebra $\mathfrak{g} \otimes \mathbb{R}$, and this bilinear form can be restricted to the Lie-algebra $\mathfrak{u}_P \otimes \mathbb{R}$ and this provides a volume form $d_x u$ on $U(\mathbb{R})$ the above number is the volume of the nilmanifold $\Gamma_{U,\underline{g}_f} \backslash U(\mathbb{R})$ with respect to this measure.

If we are in the special case that $G = \mathrm{Sl}_2/\mathbb{Q}$ and $K_f = \mathrm{Sl}_2(\hat{\mathbb{Z}})$ then a parabolic subgroup P is a point $r = \frac{p}{q} \in \mathbb{P}^1(\mathbb{Q})$ (or ∞) and then $p(P,(z,1))$ is small if z lies in a small Farey circle, i.e. it is close to r.

These numbers have some obvious properties

a) They are invariant under conjugation by an element $a \in G(\mathbb{Q})$, this means we have

$$p(a^{-1}Pa, (x, \underline{g}_f)) = p(P, a(x, \underline{g}_f))$$

b) If $\underline{p} \in P(\mathbb{A})$ then we have

$$p(P, \underline{p}(x, \underline{g}_f)) = p(P, (x, \underline{g}_f))|\rho_P|^2$$

The $G(\mathbb{Q})$ conjugacy classes of parabolic are in one to one correspondence with the subsets π' of the set relative simple roots π_G :The minimal parabolic corresponds to the empty set, the non proper parabolic subgroup $G/\mathbb{Q}$ corresponds to π_G itself. In general π' is the set of relative simple roots of the semi simple part of the reductive quotient of the parabolic subgroup. For a parabolic subgroup P' corresponding to π' we put $d(P') = \#(\pi_G \setminus \pi')$. For any $i \in \pi_G \setminus \pi'$ we have a fundamental character

$$\gamma_i : P \to \mathbb{G}_m.$$

We have the Borel-Serre compactification

$$i : \mathcal{S}^G_{K_f} \to \bar{\mathcal{S}}^G_{K_f}$$

The compactification is a manifold with corners, the boundary is stratified

$$\partial(\bar{\mathcal{S}}^G_{K_f}) = \bigcup_P \partial_P(\bar{\mathcal{S}}^G_{K_f})$$

where P runs over the $G(\mathbb{Q})$ conjugacy classes of parabolic subgroups. If $P \subset Q$ then the stratum $\partial_Q(\bar{\mathcal{S}}^G_{K_f}) \subset \overline{\partial_P(\bar{\mathcal{S}}^G_{K_f})}$.

Locally at a point $x \in \partial_P(\bar{\mathcal{S}}^G_{K_f})$ we find neighborhoods of x in $\bar{\mathcal{S}}^G_{K_f}$ which are of the form

$$U_x = W_x \times \{\dots, u_i, \dots\}_{i \in \pi_G \setminus \pi';\, 0 \le u_i < \epsilon} \tag{6.16}$$

where W_x is a neighborhood of x in the orbifold $\partial_P(\bar{\mathcal{S}}^G_{K_f})$. The intersection $\overset{\circ}{U}_x = U_x \cap \mathcal{S}^G_{K_f}$ consists of those elements where all the $u_i > 0$.

6.1.5 The easiest but very important example

If we take for instance $\mathbb{G}/\mathbb{Z} = \mathrm{Gl}_2/\mathbb{Z}$ and if we pick an integer N then we can define the congruence subgroup $K_f(N) = \prod_p K_p(N) \subset \mathbb{G}(\hat{\mathbb{Z}})$. It is defined by the condition that at all primes p dividing N the subgroup

$$K_p(N) = \{\gamma \in \mathbb{G}(\hat{\mathbb{Z}}) | \gamma \equiv \mathrm{Id} \mod p^{n_p}\}$$

where of course p^{n_p} is the exact power of p dividing N. At the other primes we take the full group of integral points. For the discussion of the example we put $K_f(N) = K_f$.

If we consider the action of $G(\mathbb{Q})$ on $G(\mathbb{A}_f)/K_f$ then the determinant gives us a map

$$\mathrm{Gl}_2(\mathbb{Q})\backslash \mathrm{Gl}_2(\mathbb{A}_f)/K_f \to \mathbb{G}_m(\mathbb{A}_f)/\mathbb{Q}^*\mathfrak{U}_N$$

where $\mathfrak{U}_N$ is the group of unit ideles in $I_{\mathbb{Q},f} = \mathbb{G}_m(\mathbb{A}_f)$ which satisfy $u_p \equiv 1 \mod p^{n_p}$. This map is a bijection as one can easily see from strong approximation in Sl_2, and the right hand side is equal to $(\mathbb{Z}/N\mathbb{Z})^*/\{\pm 1\}$. At the infinite place we have that our symmetric space has two connected components, we have

$$X = \mathrm{Gl}_2(\mathbb{R})/SO(2) = \mathbb{C} \setminus \mathbb{R} = \mathbb{H}_+ \cup \mathbb{H}_-$$

where $\mathbb{H}_\pm$ are the upper and lower half plane, respectively. We have a complex structure on X which is invariant under the action of $\mathrm{Gl}_2(\mathbb{R})$. The connected components of this quotient correspond (one to one)to the elements in

$$\mathbb{G}_m(\mathbb{A})/\mathbb{G}_m(\mathbb{Q})(\mathbb{G}_m(\mathbb{R})^0 \times \mathfrak{U}_N) = I_{\mathbb{Q}}/\mathbb{Q}^*\mathbb{R}^*_{>0}\mathfrak{U}_N = (\mathbb{Z}/N\mathbb{Z})^*.$$

We put $\Gamma(N) = G(\mathbb{Q}) \cap K_f$ and then the components are

$$\Gamma(N)\backslash \begin{pmatrix} \underline{t}_\infty & 0 \\ 0 & 1 \end{pmatrix} H_+ \times \begin{pmatrix} \underline{t}_f & 0 \\ 0 & 1 \end{pmatrix} K_f/K_f$$

where $\underline{t}$ runs through a set of representatives of $I_{\mathbb{Q}}/\mathbb{Q}^*\mathbb{R}^*_{>0}\mathfrak{U}_N = (\mathbb{Z}/N\mathbb{Z})^*$.

These connected components are Riemann surfaces which are not compact. They can be compactified by adding a finite number of points, the so called *cusps*. These are in one to one correspondence with the orbits of $\Gamma(N)$ on $\mathbb{P}^1(\mathbb{Q})$ (see reduction theory).

(Compare to Borel-Serre)

6.2 The sheaves and their cohomology

6.2.1 Basic data and simple properties

Let $\mathcal{M}$ be a finite dimensional $\mathbb{Q}$-vector space, let

$$r : G/\mathbb{Q} \to \mathrm{Gl}(\mathcal{M})$$

a rational representation. This representation r provides a sheaf $\tilde{\mathcal{M}}$ on $\mathcal{S}^G_{K_f}$ whose sections on an open subset $V \subset \mathcal{S}^G_{K_f}$ are given by

$$\tilde{\mathcal{M}}(V) = \{s : \pi^{-1}(V) \to \mathcal{M} | s \text{ locally constant and } s(\gamma v) = r(\gamma)s(v), \gamma \in G(\mathbb{Q})\}.$$

We call this the *right module description* of $\tilde{\mathcal{M}}$.

We can describe the stalk of the sheaf in a point $y \in \mathcal{S}^G_{K_f}$, we choose a point $\underline{x} = (x_\infty, \underline{g}_f)$ in $\pi^{-1}(y)$ and we choose a neighborhood V_y as in 1.2.1. Then we can evaluate an element $s \in \tilde{\mathcal{M}}(V_y)$ at $\underline{x}$ and this must be an element in $\mathcal{M}^{\Gamma_{x_\infty}}$, this means we get an isomorphism

$$e_{\underline{x}} : \tilde{\mathcal{M}}_y \xrightarrow{\sim} \mathcal{M}^{\Gamma_{x_\infty}}.$$

By definition we have $e_{\gamma\underline{x}} = \gamma e_{\underline{x}}$.

In our previous example such a representation r is of the following form: We take the homogeneous polynomials $P(X,Y)$ of degree n in two variables and with coefficients in $\mathbb{Q}$. This is a $\mathbb{Q}$-vector space of dimension $n+1$, we choose another integer m and now we define an action of $\mathrm{Gl}_2/\mathbb{Q}$ on this vector space

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} P(X,Y) = P(aX+cY, bX+dY)\det(\begin{pmatrix} a & b \\ c & d \end{pmatrix})^m.$$

This Gl_2 module will be called $\mathcal{M}_n[m]$ and it yields sheaves $\tilde{\mathcal{M}}_n[m]$ on our space $\mathcal{S}^G_{K_f}$.

It is sometimes reasonable to start from an absolutely irreducible representation and therefore we consider representations defined after a base change $r : G \times_{\mathbb{Q}} F \to \mathrm{Gl}(\mathcal{M})$ where $\mathcal{M}$ is a finite dimensional F vector space and the action is absolutely irreducible. Since $G(\mathbb{Q})$ acts on $\mathcal{M}$ we can define a sheaf $\tilde{\mathcal{M}}$ of F vector spaces.

If our group is a torus $T/\mathbb{Q}$, then we can find a finite normal extension $E/\mathbb{Q}$ such that $T \times_{\mathbb{Q}} E$ is split and then we denote by

$$X^*(T) = \mathrm{Hom}(T \times E, \mathbb{G}_m) \text{ resp } X_*(T) = \mathrm{Hom}(\mathbb{G}_m, T \times_{\mathbb{Q}} E) \tag{6.17}$$

the character (resp.) cocharacter module of $T/\mathbb{Q}$. Both modules come with an action of the Galois group $\mathrm{Gal}(E/\mathbb{Q})$. In this case an absolutely irreducible representation is simply a character $\gamma \in X^*(T)$ and we denote by $E[\gamma]$ a one dimensional E-vector space on which $T/\mathbb{Q}$ acts by γ. Then $\widetilde{E[\gamma]}$ is a sheaf of F-vector spaces on $S^T_{K^T_f}$.

Integral coefficient systems

We assume again that we have a rational representation of our group $G/\mathbb{Q}$, the following considerations easily generalize to the case of an arbitrary number field as base field. We want to define a subsheaf $\tilde{\mathcal{M}}_{\mathbb{Z}} \subset \tilde{\mathcal{M}}$. To do this we embed the field $\mathbb{Q} \hookrightarrow \mathbb{A}_f$ and we consider the resulting sheaf of $\mathbb{A}_f$-modules $\tilde{\mathcal{M}} \otimes \mathbb{A}_f$. We consider the diagram

$$
\begin{tikzcd}
 & G(\mathbb{R})/K_\infty \times (G(\mathbb{A}_f)/K_f) \arrow[dr, "\pi"] & \\
G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f) \arrow[ur, "\pi'"] \arrow[rr, "\Pi"] \arrow[dr, "\Pi_1"'] & & \mathcal{S}^G_{K_f} \\
 & G(\mathbb{Q})\backslash G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f) \arrow[ur, "\Pi_2"'] &
\end{tikzcd}
\tag{6.18}
$$

this means that the division by the action by K_f on the right and by $G(\mathbb{Q})$ on the left (this gives Π) is divided into two steps: In the lower diagram the projection Π_1 is division by the action of $G(\mathbb{Q})$ and then Π_2 gives the division by the action of K_f on the right.

The sheaf $\tilde{\mathcal{M}} \otimes_{\mathbb{Q}} \mathbb{A}_f$ can be rewritten. For any open subset $V \subset \mathcal{S}^G_{K_f}$ we consider $W = \Pi^{-1}(V)$ and by definition

$$\tilde{\mathcal{M}} \otimes_{\mathbb{Q}} \mathbb{A}_f(V) = \{s : \Pi^{-1}(W) \to \mathcal{M} \otimes_{\mathbb{Q}} \mathbb{A}_f | s(\gamma(x_\infty, \underline{g}_f \underline{k}_f)) = \gamma(s(x_\infty, \underline{g}_f)),$$

where these sections s are locally constant in the variable x_∞. For any $s \in \mathcal{M} \otimes \mathbb{A}_f(V)$ we define a map $\tilde{s} : W \to \mathcal{M} \otimes \mathbb{A}_f$ by the formula

$$\tilde{s}(x_\infty, \underline{g}_f) = \underline{g}_f^{-1} s(x_\infty, \underline{g}_f \underline{K}_f),$$

this makes sense because $\mathcal{M} \otimes \mathbb{A}_f$ is a $G(\mathbb{A}_f)-$ module. For $\gamma \in G(\mathbb{Q})$ we have $\tilde{s}(\gamma(x_\infty, \underline{g}_f)) = \tilde{s}((x_\infty, \underline{g}_f))$ hence we can view $\tilde{s}$ as a map

$$\tilde{s} : G(\mathbb{Q})\backslash G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f) \to \mathcal{M} \otimes_{\mathbb{Q}} \mathbb{A}_f.$$

We consider the projection

$$\Pi_2 : G(\mathbb{Q})\backslash G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f) \to G(\mathbb{Q})\backslash G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f = \mathcal{S}^G_{K_f}$$

and then it becomes clear that $\tilde{\mathcal{M}} \otimes \mathbb{A}_f$ can be described as

$$\widetilde{\mathcal{M} \otimes \mathbb{A}_f}(V) = \{\tilde{s} : (\Pi_1^{-1}(V) \to \mathcal{M} \otimes_{\mathbb{Q}} \mathbb{A}_f |$$
$$\tilde{s} \text{ locally constant in } x_\infty \text{ and } \tilde{s}((x_\infty, \underline{g}_f \underline{k}_f)) = \underline{k}_f^{-1} \tilde{s}((x_\infty, \underline{g}_f))\}.$$

Hence we have identified the sheaf $\tilde{\mathcal{M}} \otimes_{\mathbb{Q}} \mathbb{A}_f$ which is defined in terms of the action of $G(\mathbb{Q})$ on $\mathcal{M}$ to the sheaf $\widetilde{\mathcal{M} \otimes_{\mathbb{Q}} \mathbb{A}_f}$ which is defined in terms of the action of K_f on $\mathcal{M} \otimes_{\mathbb{Q}} \mathbb{A}_f$.

Now we assume that our group scheme $G/\mathbb{Q}$ is the generic fiber of a flat group scheme $\mathbb{G}/\operatorname{Spec}(\mathbb{Z})$ (See 1.2). We choose our maximal compact subgroup $K_f = \prod_p K_p$ such that $K_p \subset \mathbb{G}(\mathbb{Z}_p)$ and with equality for all primes outside a finite set Σ. We can extend the vector space $\mathcal{M}$ to a free $\mathbb{Z}$ module $\tilde{\mathcal{M}}_\mathbb{Z}$ of the same rank which provides a representation $\mathbb{G}/\operatorname{Spec}(\mathbb{Z}) \to \mathrm{Gl}(\mathcal{M}_\mathbb{Z})$.

As usual $\hat{\mathbb{Z}}$ will be the ring of integral adeles. Then it is clear that $\mathcal{M}_\mathbb{Z} \otimes \hat{\mathbb{Z}} \subset \mathcal{M} \otimes_\mathbb{Q} \mathbb{A}_f$ is invariant under K_f and hence we can define the sub sheaf

$$\widetilde{\mathcal{M}_\mathbb{Z} \otimes \hat{\mathbb{Z}}} \subset \mathcal{M}\widetilde{\otimes_\mathbb{Q}} \mathbb{A}_f,$$

this is the sheave where the sections $\tilde{s}$ have values in $\mathcal{M}_\mathbb{Z} \otimes \hat{\mathbb{Z}}$. We put

$$\tilde{\mathcal{M}}_\mathbb{Z} = \widetilde{\mathcal{M}_\mathbb{Z} \otimes \hat{\mathbb{Z}}} \cap \tilde{\mathcal{M}},$$

of course it depends on our choice of $\mathcal{M}_\mathbb{Z} \subset \mathcal{M}$. We get two exact sequences of sheaves

$$\begin{array}{ccccccc} 0 & \to & \tilde{\mathcal{M}}_\mathbb{Z} & \to & \tilde{\mathcal{M}} & \to & \mathcal{M}\widetilde{\otimes (\mathbb{Q}/\mathbb{Z})} \to 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \to & \widetilde{\mathcal{M} \otimes \hat{\mathbb{Z}}} & \to & \mathcal{M}\widetilde{\otimes_\mathbb{Q}} \mathbb{A}_f & \to & \mathcal{M}\widetilde{\otimes (\mathbb{A}_f}/\hat{\mathbb{Z}}) \to 0 \end{array}$$

The far most vertical arrow to the right is an isomorphism, the inclusions $\mathbb{Z} \hookrightarrow \hat{\mathbb{Z}}$ and $\mathbb{Q} \hookrightarrow \mathbb{A}_f$ are flat. Writing down the resulting long exact sequences provides a diagram

$$\begin{array}{ccccc} \to & H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}) & \xrightarrow{j_\mathbb{Q}} & H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) & \to \\ & \downarrow i_\mathbb{Z} & & \downarrow i_\mathbb{Q} & . \\ \to & H^\bullet(\mathcal{S}^G_{K_f}, \widetilde{\mathcal{M} \otimes \hat{\mathbb{Z}}}) & \xrightarrow{j_\mathbb{A}} & H^\bullet(\mathcal{S}^G_{K_f}, \mathcal{M}\widetilde{\otimes_\mathbb{Q}} \mathbb{A}_f) & \to \end{array}$$

The above remarks imply that the vertical arrows are injective, the horizontal arrows in the middle have the same kernel and kokernel. This implies

Proposition 6.2.1. *The integral cohomology*

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z})$$

consists of those elements in $H^\bullet(\mathcal{S}^G_{K_f}, \widetilde{\mathcal{M} \otimes \hat{\mathbb{Z}}})$ which under $j_\mathbb{A}$ go to an element in the image under $i_\mathbb{Q}$ or in brief

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}) = j_\mathbb{A}^{-1}(\mathrm{im}(i_\mathbb{Q}))$$

This generalizes to the case where we have a representation $r : G \times F \to \mathrm{Gl}(\mathcal{M})$ where $\mathcal{M}$ is a vector space over F. If our group scheme is an extension of a flat group scheme $\mathcal{G}/\operatorname{Spec}(\mathcal{O}_F)$ then can find a lattice $\mathcal{M}_{\mathcal{O}_F}$ which yields a representation of $\mathcal{G} \to \mathrm{Gl}(\mathcal{M}_{\mathcal{O}_F})$. Then we can define the sheaf $\tilde{\mathcal{M}}_{\mathcal{O}_F}$ and define the cohomology groups

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})$$

Sheaves with support conditions

We can extend the sheaves to the Borel-Serre compactification. We have the inclusion

$$i : \mathcal{S}^G_{K_f} \to \bar{\mathcal{S}}^G_{K_f}$$

and we can extend the sheaf by the direct image functor $i_*(\tilde{\mathcal{M}})$. It follows easily from the description of the neighborhood of a point in the boundary (see 6.16) that $R^q i_*(\mathcal{M}) = 0$ for $q = 0$ and hence we get that the restriction map

$$H^\bullet(\bar{\mathcal{S}}^G_{K_f}, i_*(\tilde{\mathcal{M}})) \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$$

is an isomorphism.

We may also extend the sheaf by zero (See [Vol I], 4.7.1), this yields the sheaf $i_!(\tilde{\mathcal{M}})$ whose stalk at $x \in \mathcal{S}^G_{K_f}$ is equal to $\tilde{\mathcal{M}}_x$ and whose stalk ist zero in points $x \in \partial\mathcal{S}^G_{K_f}$. Then we have by definition

$$H^\bullet_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) = H^\bullet(\bar{\mathcal{S}}^G_{K_f}, i_!(\tilde{\mathcal{M}}))$$

this is the cohomology with compact supports.

We are interested in the *integral* cohomology modules $H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}), H^\bullet_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z})$. We introduced the boundary $\partial\mathcal{S}^G_{K_f}$ of the Borel-Serre compactification then we have a first general theorem, which is due to Raghunathan.

Theorem 6.2.1. *(i) The cohomology groups* $H^i(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}), H^i(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z})$ *and* $H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z})$ *are finitely generated.*

(ii) We have the well known **fundamental long exact sequence** *in cohomology*

$$\longrightarrow H^{i-1}(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}) \longrightarrow H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}) \longrightarrow H^i(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}) \xrightarrow{r} H^i(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}) \longrightarrow .$$

We introduce the notation $H_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z})$ meaning that for $? =$ blank we take the cohomology without support, for $? = c$ we take the cohomology with compact support and for $? = \partial$ we take cohomology of the boundary of the Borel-Serre compactification. Later on we will also allow $? =!$ this denotes the inner cohomology. The above proposition holds for all choices of ?.

Let $\Sigma = \{P_1, \dots, P_s\}$ be a finite set of parabolic subgroups, we assume that none of them is a subgroup of another parabolic subgroup in this set. The union of the closures of the strata

$$\bigcup_i \bigcup_{Q \subset P_i} \partial_Q(\mathcal{S}^G_{K_f}) = \partial_\Sigma(\mathcal{S}^G_{K_f})$$

is closed .

$$j_\Sigma : \mathcal{S}^G_{K_f} \to \bar{\mathcal{S}}^G_{K_f} \setminus \partial_\Sigma(\bar{\mathcal{S}}^G_{K_f}), j^\Sigma : \bar{\mathcal{S}}^G_{K_f} \setminus \partial_\Sigma(\bar{\mathcal{S}}^G_{K_f}) \to \bar{\mathcal{S}}^G_{K_f}.$$

The inclusion $i : \mathcal{S}^G_{K_f} \to \bar{\mathcal{S}}^G_{K_f}$ is the composition $i = j^\Sigma \circ j_\Sigma$ we define the intermediate extension

$$i_{\Sigma,*,!}(\tilde{\mathcal{M}}) = j^\Sigma_! \circ j_{\Sigma,*}(\tilde{\mathcal{M}}). \tag{6.19}$$

For these sheaves with intermediate support conditions we can also formulate assertion like in the above theorem. Later we will discuss an increasing filtration

$$W_0 H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) = H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) \subset W_1 H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) \subset \dots \tag{6.20}$$

on the cohomology, the bottom of this filtration will be the inner cohomology,

Functorial properties

The groups have some functorial properties if we vary the level subgroup K_f. If we pass to a smaller open subgroup $K'_f \subset K_f$ then we get a surjective map

$$\pi_{K_f,K'_f} : \mathcal{S}^G_{K'_f} \to \mathcal{S}^G_{K_f},$$

whose fibers are finite. This induces maps between cohomology groups

$$\pi_{K'_f,K_f}{}^{\bullet}_{?} : H^\bullet_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z}) \to H^\bullet_?(\mathcal{S}^G_{K'_f}, \tilde{\mathcal{M}}_\mathbb{Z}),$$

for $? = c$ we exploit the fact that the fibers are finite.

We construct homomorphisms in the opposite direction. We exploit the finiteness a second time and find that the direct image functor $(\pi_{K'_f,K_f})_*$ is exact and hence

$$H^\bullet_?(\mathcal{S}^G_{K'_f}, \tilde{\mathcal{M}}_\mathbb{Z}) = H^\bullet_?(\mathcal{S}^G_{K_f}, (\pi_{K'_f,K_f})_*(\tilde{\mathcal{M}}_\mathbb{Z})).$$

We define a trace homomorphism $(\pi_{K'_f,K_f})_*(\tilde{\mathcal{M}}_\mathbb{Z}) \to \tilde{\mathcal{M}}_\mathbb{Z}$: A section $s \in (\pi_{K'_f,K_f})_*(\tilde{\mathcal{M}}_\mathbb{Z})(V)$ is a map $\tilde{s} : \Pi^{-1}(V) \to \tilde{\mathcal{M}}_\lambda \otimes \hat{\mathbb{Z}}$ such that

$$\tilde{s}(\gamma(x_\infty, \underline{g}_f \underline{k}'_f)) = (k'_f)^{-1} \tilde{s}((x_\infty, \underline{g}_f)) \text{ for all } k'_f \in K'_f.$$

This is a section of $\tilde{\mathcal{M}}_\mathbb{Z}$ if and only if the corresponding section s takes values in $\mathcal{M}$. Then we define

$$\mathrm{tr}(\tilde{s})(x_\infty, \underline{g}_f) = \sum_{\underline{\xi}_f \in K_f/K'_f} \underline{\xi}_f^{-1} \tilde{s}(x_\infty, \underline{g}_f)$$

and this now satisfies

$$\mathrm{tr}(\tilde{s})(\gamma(x_\infty, \underline{g}_f \underline{k}_f)) = k_f^{-1} \tilde{s}((x_\infty, \underline{g}_f)) \text{ for all } k_f \in K_f.$$

and since the corresponding section $\mathrm{tr}(s)$ takes values in $\mathcal{M}$ we see that $\mathrm{tr}(\tilde{s}) \in \tilde{\mathcal{M}}_\mathbb{Z}(V)$.

Remark: It may happen that this trace map is not the optimal choice, it can be the integral multiple of another homomorphism between these two sheaves. This happens the intersection $C(\mathbb{Q}) \cap K_f$ is non trivial.

Then the homomorphism between the sheaves induces

$$H^\bullet_?(\mathcal{S}^G_{K'_f}, \tilde{\mathcal{M}}_\mathbb{Z}) = H^\bullet_?(\mathcal{S}^G_{K_f}, (\pi_{K'_f,K_f})_*(\tilde{\mathcal{M}}_\mathbb{Z})) \xrightarrow{\pi_{K'_f,K_f}} {}^\bullet\, H^\bullet_?(\mathcal{S}^G_{K_f}, (\tilde{\mathcal{M}}_\mathbb{Z})).$$

Later on our maps between the spaces will be denoted $\pi, \pi_1, \ldots$ and the notation simplifies accordingly.

6.3 The action of the Hecke-algebra

6.3.1 The action on rational cohomolgy

In this section we assume that our coefficient systems are obtained from rational representations of a reductive group scheme $G/\mathbb{Q}$ hence they are $\mathbb{Q}$ vector spaces.

We discuss some further properties of the *rational* cohomology groups

$$H^i_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathbb{Q}}), H^i(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathbb{Q}})\dots.$$

These cohomology groups are finite dimensional $\mathbb{Q}$-vector spaces and we have the same exact fundamental sequence. We can also pass to the direct limit

$$H^i_?(\mathcal{S}^G,\tilde{\mathcal{M}}) = \lim_{K_f} H^i_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}).$$

Proposition 6.3.1. *On these limits we have an action of the group* $\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)$. *We recover the cohomology with fixed level* K_f *by taking the invariants under this action, i.e. we have*

$$H^i_?(\mathcal{S}^G,\tilde{\mathcal{M}})^{K_f} = H^i_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})$$

To define this action we represent an element in $\pi_0(G(\mathbb{R}))$ by an element k_∞ in the in the normalizer of K_∞ in $G(\mathbb{R})$. An element $\underline{x} = (k_\infty,\underline{x}_f) \in G(\mathbb{R})\times G(\mathbb{A}_f))$ defines by multiplication from the right an isomorphism of spaces

$$m_{\underline{x}} : G(\mathbb{Q})\backslash X\times G(\mathbb{A}_f)/K_f \xrightarrow{\sim} G(\mathbb{Q})\backslash X\times G(\mathbb{A}_f)/\underline{x}_f^{-1}K_f\underline{x}_f.$$

It is clear from the definition that $m_{\underline{x}}$ yields a bijection between the fibers $\pi^{-1}(\underline{\bar{g}}), \underline{\bar{g}}\in G(\mathbb{Q})\backslash X\times G(\mathbb{A}_f)/K_f$ and $\pi^{-1}(m_{\underline{x}})(\underline{\bar{g}})$ and since the sheaf is described in terms of the left action by $G(\mathbb{Q})$ we get $m_{\underline{x},*}(\tilde{\mathcal{M}}) = \tilde{\mathcal{M}}$. Passing to the limit gives us the action. The second assertion is obvious, but here we need that our coefficients are $\mathbb{Q}$ vector spaces, we need to take averages.

We introduce the Hecke algebra, it acts on the cohomology with a fixed level. It consists of the compactly supported $\mathbb{Q}-$valued functions $h : G(\mathbb{A}_f)\to\mathbb{Q}$ which are biinvariant under the action of K_f and is denoted by $\mathcal{H} = \mathcal{H}_{K_f} = \mathcal{C}_c(G(\mathbb{A}_f)//K_f,\mathbb{Q})$. An element $h\in\mathcal{H}$ is simply a finite linear combination of characteristic functions $h = \sum c_{\underline{a}_f}\chi_{K_f\underline{a}_fK_f}$ with rational coefficients $c_{\underline{a}_f}$. The algebra structure is given by convolution with respect to the Haar measure on $G(\mathbb{A}_f)$ which gives volume 1 to K_f. This convolution is given by

$$h_1 * h_2(\underline{g}_f) = \int_{G(\mathbb{A}_f)} h_1(\underline{x}_f)h_2({\underline{x}_f}^{-1}\underline{g}_f)d\underline{x}_f.$$

With this choice of the measure it is clear that the characteristic function of K_f is the identity element of this algebra.

The action of the group $G(\mathbb{A}_f)$ induces an action of $\mathcal{H}_{K_f}$ on the cohomology with fixed level $H^i_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}), H^i(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}),\cdots$: For an element $v\in H^i_?(\mathcal{S}^G,\tilde{\mathcal{M}})$ we define

$$T_h(v) = \int_{G(\mathbb{A}_f)} h(\underline{x}_f)\underline{x}_f v d\underline{x}_f,$$

where the measure is still the one that gives volume 1 to K_f. Clearly we have $T_{h_1*h_2} = T_{h_1}T_{h_2}$.

(Actually the integral is a finite sum: We find an open subgroup $K'_f\subset K_f$ such that v is fixed by K'_f and then it is clear that

$$T_h(v) = \int_{G(\mathbb{A}_f)} h(\underline{x}_f)\underline{x}_f v d\underline{x}_f = \mathtt{1}[K_f:K'_f]\sum_{\underline{a}_f}\sum_{\underline{\xi}_f\in G(\mathbb{A}_f)/K'_f} c_{\underline{a}_f}\chi_{K_f\underline{a}_fK_f)}(\underline{\xi}_f)\underline{\xi}_f v.$$

This makes it clear why we need rational coefficients .)

It is clear that $T_h(v) \in H^i_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ and hence T_h gives us an endomorphism of $H^i_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$. We will show later that we also get endomorphisms on the cohomology of the boundary and therefore $\mathcal{H}$ also acts on the long exact sequence (Seq) .

If our function h is the characteristic function of a double coset $K_f \underline{x}_f K_f$ then we change notation and write $T_h = \mathbf{ch}(\underline{x}_f)$. We give another definition of the Hecke operator $\mathbf{ch}(\underline{x}_f)$ in terms of sheaf cohomology. We imitate the construction of the Hecke operators in Chap.II 2.2. We put $K_f^{(\underline{x}_f)} = K_f \cap \underline{x}_f K_f \underline{x}_f^{-1}$ and consider the diagram

$$\begin{array}{ccccc} S^G_{K_f^{(\underline{x}_f)}} & & \xrightarrow{m_{\underline{x}_f}} & & S^G_{K_f^{(\underline{x}_f^{-1})}} \\ & \searrow \pi_1 & & \swarrow \pi_2 & \\ & & \mathcal{S}^G_{K_f} & & \end{array} \qquad Hop1$$

where $m_{\underline{x}_f}$ is induced by the multiplication by $\underline{x}_f$ from the right. This yields in cohomology

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) \xrightarrow{\pi_1^\bullet} H^\bullet(S^G_{K_f^{(\underline{x}_f)}}, \tilde{\mathcal{M}}) \xrightarrow{m_{\underline{x}_f,*}} H^\bullet(S^G_{K_f^{(\underline{x}_f^{-1})}}, m_{\underline{x}_f,*}(\tilde{\mathcal{M}})) \qquad (Hop2).$$

Since we described the sheaf by the action of $G(\mathbb{Q})$ and the map $m_{\underline{x}_f}$ by multiplication from the right we have $m_{\underline{x}_f,*}(\tilde{\mathcal{M}}) = \tilde{\mathcal{M}}$, this yields an isomorphism $i_{\underline{x}_f}$. Since π_2 is finite we have the trace homomorphism

$$\pi_{2,\bullet} : H^\bullet(S^G_{K_f^{(\underline{x}_f)^{-1}}}, \tilde{\mathcal{M}}) \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$$

and the composition is our Hecke operator

$$\pi_{2,\bullet} \circ i_{\underline{x}_f} \circ m_{\underline{x}_f,*} \circ \pi_1^\bullet = \mathbf{ch}(\underline{x}_f) : H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}).$$

This is simpler than the construction Chap.II 2.2. because we do not need the intermediate homomorphism u_α. But we we do not get Hecke operators on the integral cohomology.

6.3.2 The integral cohomology as a module under the Hecke algebra

We resume the discussion of the integral Hecke algebra acting on $H^\bullet_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\mathbb{Z})$ from Chapter II. Inside the Hecke algebra we may also look at the sub algebra of $\mathbb{Z}$ -valued functions. This is in principle the algebra which is generated by the characteristic functions $\mathbf{ch}(\underline{x}_f)$ of double cosets $K_f \underline{x}_f K_f$. These characteristic functions act by convolution on the cohomology $H^\bullet(\mathcal{S}^G_{K_f}, \mathcal{M})$ but this does not induce an action on the integral cohomology. Our next aim is to define a fractional ideal $\mathfrak{n}(\underline{x}_f) \subset \mathbb{Q}$ or more generally $\mathfrak{n}(\underline{x}_f) \subset F$ such that for any $a \in \mathfrak{n}(\underline{x}_f)$ we can define an endomorphism

$$a \cdot \mathbf{ch}(\underline{x}_f) : H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda\ )$$

and if we send this to the rational cohomology then on $H^\bullet(\mathcal{S}^G_{K_f}, \mathcal{M})$ this will be the convolution endomorphism induced by $\mathbf{ch}(\underline{x}_f)$ multiplied by a.

This ideal will depend on $\underline{x}_f$ and on λ and further down we compute it in special cases.

(iv) These endomorphisms $a \cdot \mathbf{ch}(\underline{x}_f)$ generate an algebra $\mathcal{H}^{(\lambda)}_{\mathbb{Z}}$ acting on the integral cohomology and the arrows in our sequence above commute with this action.

v) Moreover, we have an action of $\pi_0(G(\mathbb{R}))$ on the above sequence and this action also commutes with the action of the Hecke algebra. Hence we know that our above sequence is long exact sequence of $\pi_0(G(\mathbb{R})) \times \mathcal{H}^{(\lambda)}_{\mathbb{Z}}$.

We come to the definition of the ideal.

If we are in the special case that our group has strong approximation then we have

$$\Gamma\backslash X \xrightarrow{\sim} G(\mathbb{Q})\backslash X \times G(\mathbb{A}_f)/K_f$$

(See (6.10)). We pick an element $\alpha \in G(\mathbb{Q})$. In Chap. II , 2.2 we defined the Hecke operator $T(\alpha, u_\alpha)$ where $u_\alpha : \mathcal{M}^{(\alpha)} \to \mathcal{M}$ is the canonical choice. Let us denote the image of α in $G(\mathbb{A}_f)$ by $\underline{\alpha}_f$. We just attached a Hecke operator to the double coset $K_f\underline{\alpha}_f.K_f$. We have the diagram of spaces

$$\begin{tikzcd}
\Gamma(\alpha)\backslash X \arrow[r] \arrow[d, "l(\alpha^{-1})"] & G(\mathbb{Q})\backslash G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f^{\underline{\alpha}_f} \arrow[d, "r(\underline{\alpha}_f)"] \\
\Gamma(\alpha^{-1})\backslash X \arrow[r] & G(\mathbb{Q})\backslash G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f^{\underline{\alpha}_f^{-1}}
\end{tikzcd} \tag{6.21}$$

Here the horizontal arrows are the isomorphisms provided by strong approximation, the arrow $l(\alpha^{-1})$ is the isomorphism induced by left multiplication by α^{-1} and $r(\underline{\alpha}_f)$ by right multiplication by $\underline{\alpha}_f$. These two maps enter in the definition of the Hecke operators $T(\alpha^{-1}, u_{\alpha^{-1}})$ and $\mathbf{ch}(\underline{\alpha}_f)$ and a straightforward inspection of the sheaves yields

$$\mathbf{ch}(\underline{\alpha}_f) = T(\alpha^{-1}, u_{\alpha^{-1}}).$$

Hence we can conclude that under this assumption our newly defined Hecke operators coincide with the Hecke operators defined in Chap. II. This also tells us what we have to do if we want to define Hecke operators on integral cohomology.

To define the action of the Hecke algebra on the integral cohomology without the assumption of simple connectedness we have to translate their definition into the right module description. Then our sheaf $\widetilde{\mathcal{M} \otimes \mathbb{A}_f}$ is described by the action of K_f on $\mathcal{M} \otimes \mathbb{A}_f$ and this allows us to define the sub sheaf $\mathcal{M}_{\mathbb{Z}} \otimes \hat{\mathbb{Z}}$. We look at the same diagram. But now the sheaf $m_{\underline{x}_f,*}(\widetilde{\mathcal{M} \otimes \mathbb{A}_f})$ is the sheaf described by the the $K_f^{(\underline{x}_f)^{-1}}$ module $(\mathcal{M}\otimes\mathbb{A}_f)^{(\underline{x}_f)}$. This module is $\mathcal{M}\otimes\mathbb{A}_f$ as abelian group, but $\underline{g}_f \in K_f^{(\underline{x}_f)^{-1}}$ acts by $\underline{m}_f \mapsto \underline{x}_f \underline{g}\underline{x}_f^{-1}\underline{m}_f$. The map $\underline{m}_f \to \underline{x}_f\underline{m}_f$ induces an isomorphism $[\underline{x}_f]$ between the two $K_f^{(\underline{x}_f)^{-1}}$ modules $(\mathcal{M}\otimes\mathbb{A}_f)^{(\underline{x}_f)}$ and $(\mathcal{M}\otimes\mathbb{A}_f)$. We now consider the diagram $Hop1$. and replace in the sequence of maps the homomorphism $i_{\underline{x}_f}$ by the map $[\underline{x}_f^{\bullet}]$ induced by the isomorphism $[\underline{x}_f]$ between the sheaves. Then we can proceed as before and get an operator

$$p_{1,*}\circ[\underline{x}_f]^{\bullet}\circ m_{\underline{x}_f,*}\circ p_2^* = \mathbf{ch}(\underline{x}_f).$$

It is straightforward to check that this operator is an extension $\pi_{2,\bullet}\circ i_{\underline{x}_f}\circ m_{\underline{x}_f,*}\circ\pi_1^{\bullet}$ to $H^{\bullet}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}\otimes\mathbb{A}_f)$.

Our right module sheaf contains the submodule sheaf $\tilde{\mathcal{M}}_\lambda\otimes\hat{\mathbb{Z}}$, we can write the same diagram but now it can happen that $[\underline{x}_f]$ does not map $\mathcal{M}_{\mathbb{Z}}\otimes\hat{\mathbb{Z}}$ into itself. This forces us to make the following definition

$$\mathfrak{n}(\underline{x}_f) = \{a\in\mathbb{Q}|\ [a\underline{x}_f] : \mathcal{M}_{\mathbb{Z}}\otimes\hat{\mathbb{Z}}\subset\mathcal{M}_{\mathbb{Z}}\otimes\hat{\mathbb{Z}}\}$$

Then we can again go back to our above diagram and it becomes clear that we can define Hecke operators

$$a\cdot\mathbf{ch}(\underline{x}_f) : H^{\bullet}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathbb{Z}})\to H^{\bullet}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathbb{Z}}) \text{ for all } a\in\mathfrak{n}(\underline{x}_f).$$

The case of a split group

We want to discuss this in the special case that $\mathcal{G}/\operatorname{Spec}(\mathbb{Z})$ is split reductive, we assume that the derived group $\mathbb{G}^{(1)}/\operatorname{Spec}(\mathbb{Z})$ is simply connected, we assume that the center $\mathcal{C}/\operatorname{Spec}(\mathbb{Z})$ is a (split)-torus and that $\mathcal{C}\cap\mathcal{G}^{(1)}$ is equal to the center $Z^{(1)}$ of $\mathcal{G}^{(1)}$. This center is a finite multiplicative group scheme (See 6.1.1).

Accordingly we get decompositions up to isogeny of the character and cocharacter modules of the torus

$$X^*(\mathcal{T})\hookrightarrow X^*(\mathcal{T}^{(1)})\oplus X^*(\mathcal{C})\ X_*(\mathcal{T}^{(1)})\oplus X_*(\mathcal{C})\hookrightarrow X_*(\mathcal{T}) \tag{6.22}$$

they become isomorphisms after taking the tensor product by $\mathbb{Q}$. We numerate the simple positive roots $I=\{1,2,\dots,r\}=\{\alpha_1,\alpha_2,\dots,\alpha_r\}\subset X^*(\mathcal{T})$ and we define dominant fundamental weights $\gamma_i\in X^*(\mathcal{T})_{\mathbb{Q}}$ which restricted to $\mathcal{T}^{(1)}$ are the usual fundamental dominant weights and restricted to $\mathcal{C}$ are trivial. Then a dominant weight can be written as

$$\lambda=\sum_{i\in I}a_i\gamma_i+\delta=\lambda^{(1)}+\delta, \tag{6.23}$$

where $\delta\in X^*(\mathcal{C})$ and we must have the congruence condition

$$(\lambda^{(1)}+\delta)|Z^{(1)}=1 \tag{6.24}$$

We can construct a highest weight module $\mathcal{M}_{\lambda,\mathbb{Z}}$. We pick a prime p, we assume that is unramified (with respect to K_f), this means that $K_p=\mathcal{G}(\mathbb{Z}_p)$.

Any element $t_p \in T(\mathbb{Q}_p)$ defines a double coset $K_p t_p K_p$. Of course only the image of t_p in $T(\mathbb{Q}_p)/\mathcal{T}(\mathbb{Z}_p)$ matters and

$$T(\mathbb{Q}_p)/\mathcal{T}(\mathbb{Z}_p) = X_*(T)$$

we find $\chi \in X_*(T)$ such that $\chi(p) = t_p$. We take a χ in the positive chamber, i.e. we assume $< \chi, \alpha > \geq 0$ for all α. We can produce the element

$$\underline{\chi}_p = (1 \dots, 1, \dots, \chi(p), 1 \dots, 1, \dots) \in T(\mathbb{A}_f)$$

and the Hecke operator

$$\mathrm{ch}(\underline{\chi}_p) : H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}} \otimes \mathbb{Q}) \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}} \otimes \mathbb{Q})$$

We have to look at the ideal of those integers a for which

$$a\ \mathrm{ch}(\underline{\chi}_p)(\mathcal{M}_{\lambda,\mathbb{Z}} \otimes \mathbb{Z}_p) \subset (\mathcal{M}_{\lambda,\mathbb{Z}} \otimes \mathbb{Z}_p).$$

This is easy: We have the decomposition into weight spaces

$$\mathcal{M}_{\lambda,\mathbb{Z}} = \oplus_\mu \mathcal{M}_{\lambda,\mathbb{Z}}(\mu)$$

and on a weight space the torus element $\mathrm{ch}(\underline{\chi}_p)$ acts by

$$\mathrm{ch}(\underline{\chi}_p) x_\mu = p^{<\chi,\mu>} x_\mu.$$

We get the smallest exponent if we choose for μ, the lowest weight vector. We denote by w_0 the longest element in the Weyl group, which sends all the positive roots into negative roots. The the element $-w_0$ induces an involution $i \to i'$ on the set of simple roots. Then

$$\mu = w_0(\lambda) = -\sum a_{i'} \gamma_i + \delta. \tag{6.25}$$

We say that our weight is (essentially) *self dual* if we have $a_i = a_{i'}$. If our weight is self dual then $\mu = -\lambda^{(1)} + \delta$

Hence we see that our ideal is the principal ideal is given by

$$(p^{-<\chi, w_0 \lambda^{(1)}> - <\chi,\delta>}) \text{ or if } \lambda \text{ self dual } (p^{<\chi,\lambda^{(1)}> - <\chi,\delta>}) \tag{6.26}$$

and therefore, we have the Hecke operator

$$T^{\mathrm{coh},\lambda}_{p,\chi} = p^{-<\chi, w_0 \lambda^{(1)}> - <\chi,\delta>} \cdot \mathrm{ch}(\underline{\chi}_p) : H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,\mathbb{Z}}) \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,\mathbb{Z}}) \tag{6.27}$$

The number $- < \chi, w_0 \lambda^{(1)} >$ is the relevant contribution in the exponent (let us call this the semi-simple term), the second term $- < \chi, \delta >$ is a correction term (the abelian contribution) and it takes care of the central character. We come back to this in section 7.0.6.

6.3.3 Excursion: Finite dimensional $\mathcal{H}-$modules and representations.

We fix a level $K_f = \prod_p K_p$ and drop it in the notations. It follows from the theorem 6.2.1 that we have a finite Jordan-Hölder series on our cohomology groups such that the subquotients are irreducible Hecke-modules. If we take the tensor product with a suitable finite extension $F/\mathbb{Q}$ then we can refine the Jordan-Hölder series such that the quotients become absolutely irreducible modules for the Hecke algebra, we say a few words concerning the absolutely irreducible Hecke-modules.

We have a decomposition

$$\mathcal{H} = \bigotimes_p{}' \mathcal{H}_p = \bigotimes_p{}' \mathcal{C}_c(G(\mathbb{Q}_p)//K_p).$$

As the notation indicates we take the tensor product over all finite primes. This tensor product has to be taken in a restricted sense: for an element of the form $h_f = \otimes h_p$ the local factor h_p is equal to the identity element for almost all primes p (this is the characteristic function of K_p). All other elements are finite linear combinations of elements of the form above. We have the obvious embedding $\mathcal{H}_p \hookrightarrow \mathcal{H}$ we simply send $h_p \mapsto 1 \otimes \cdots \otimes h_p \otimes 1 \ldots$. The subalgebras $\mathcal{H}_p$ commute with each other.

We are interested in categories of modules for the Hecke algebra, which will be finite dimensional $\mathbb{Q}-$ vector spaces V together with a homomorphism $\mathcal{H} \to \operatorname{End}_{\mathbb{Q}}(V)$. If Let us call this category $\mathbf{Mod}_{\mathcal{H}}$. For any extension $L/\mathbb{Q}$ we may consider the extension $\mathcal{H}_L = \mathcal{H} \otimes L$ and the resulting category $\mathbf{Mod}_{\mathcal{H}_L}$. If we have an extension $L \hookrightarrow K$ the tensor product yields a functor $\mathbf{Mod}_{\mathcal{H}_L} \to \mathbf{Mod}_{\mathcal{H}_K}$.

We briefly recall the theory of modules over a finite dimensional $\mathbb{Q}$-algebra $\mathcal{A}$ more precisely for any extension $L/\mathbb{Q}$ we consider the category $\mathbf{Mod}_{\mathcal{A}_L}$ of finite dimensional L-vector spaces V together with a homomorphism $\mathcal{A}_L \to \operatorname{End}_L(V)$.

We say that a finite dimensional $\mathcal{A}_L$ module V irreducible, if V does not contain a non trivial $\mathcal{A}_L$ submodule. We say that V is absolutely irreducible if $V \otimes \bar{L}$ is irreducible. We say that V is indecomposable if it can not be written as the direct sum of two non zero submodules.

We call such an algebra $\mathcal{A}$ semi-simple if it does not contain a non trivial two sided ideal $\mathcal{N}$ consisting of nilpotent elements. It is well known that this is equivalent to the semi simplicity of the category $\mathbf{Mod}_{\mathcal{A}}$, this means that for any $\mathcal{A}$-module V (finite dimensional over $\mathbb{Q}$) and any submodule $W \subset V$ we can find a $\mathcal{A}$ submodule W' such that $V = W \oplus W'$. It is also well known that $\mathcal{A}$ is semi simple if it has a faithful semi-simple (finite dimensional) module $V \in \mathbf{Ob}(\mathbf{Mod}_{\mathcal{A}})$, where faithful means that $\mathcal{A} \to \operatorname{End}_{\mathbb{Q}}(V)$ is injective and semi simple means of course that any $\mathcal{A}$-submodule $W \subset V$ admits a complement.

It follows from a simple Galois-theoretic argument, that $\mathcal{A}$ is semi simple if and only if $\mathcal{A} \otimes_{\mathbb{Q}} L$ is semi simple for any extension $L/\mathbb{Q}$.

If we have two modules V_1, V_2 in $\mathbf{Mod}_{\mathcal{A}_L}$ and these modules become isomorphic after some extension $L \hookrightarrow K$, then they are already isomorphic over L. The isomorphism classes of irreducible modules for $\mathcal{A}_L$ form a set which is called $\operatorname{Spec}(\mathcal{A}_L)$. It is a standard fact from the theory of semi simple algebras that this spectrum can be identified to the set of two sided maximal ideals.

We also know that we can write the identity element as a sum of commuting idempotents

$$1 = \sum_{\phi \in \text{ Spec}(\mathcal{A}_L)} e_\phi ; e_\phi^2 = e_\phi ; e_\phi e_\psi = 0 \text{ for } \phi \neq \psi .$$

Then $\mathcal{A}_L e_\psi$ is simple, i.e. has no non trivial two sided ideal. The maximal ideal corresponding to ϕ is $\oplus_{\psi:\psi\neq\phi} \mathcal{A} e_\psi$. We have the decomposition

$$\mathcal{A}_L = \sum_{\phi \in \text{ Spec}(\mathcal{A}_L)} \mathcal{A}_L e_\phi \tag{6.28}$$

Our algebra $\mathcal{A}_L$ has a center $\mathfrak{Z}_L$, which is a commutative algebra over L and since it does not have nilpotent elements it is a direct sum of fields. The idempotents $e_\phi \in \mathfrak{Z}_L$ and clearly

$$\mathfrak{Z}_L = \oplus_{\phi \in \text{ Spec}(\mathcal{A}_L)} \mathfrak{Z} e_\phi$$

where $\mathfrak{Z}_L e_\phi$ is a field. Hence we get an identification $\text{Spec}(\mathcal{A}_L) = \text{Spec}(\mathfrak{Z}_L)$.

We conclude that a semi-simple algebra $\mathcal{A}_L$ whose center $\mathfrak{Z}_L$ is a field is actually simple and then the structure theorem of Wedderburn implies

$$\mathcal{A}_L \xrightarrow{\sim} M_n(\mathcal{D})$$

where the right hand side is a matrix algebra of a central division algebra $\mathcal{D}/\mathfrak{Z}_L$. This algebra has only one irreducible non zero module: It acts by multiplication from the left on itself, any non zero minimal left ideal yields an irreducible module. These modules (minimal left ideals) are isomorphic to the ideal given by $\mathfrak{c}_i$ where $\mathfrak{c}_i$ consists of those matrices which have zero entries outside the i-th column. In this case $\text{Spec}(\mathcal{A}_L) = (0)$ is the zero ideal. The unique irreducible module is not absolutely irreducible if $\mathcal{D} \neq \mathfrak{Z}_L$ We may choose an extension K/L which splits the division algebra, then $\mathcal{A}_F = M_{nd}(K)$ where $[\mathcal{D} : L] = d^2$. If this is the case we call the algebra $\mathcal{A}_K$ absolutely simple. The spectrum does not change.

This tells us that in general the set of isomorphism classes of irreducible $\mathcal{A}_L$ is canonically isomorphic to $\text{Spec}(\mathcal{A}_L)$ for any irreducible $\mathcal{A}_L$ module Y_ϕ we have exactly one ϕ such that $e_\phi Y = Y$, and for all $\psi \neq \phi$ $e_\psi Y = 0$. One the other hand our construction above yields exactly one module irreducible module Y_ϕ for a given ϕ. For any $\mathcal{A}_L$ -module X we get the isotypical decomposition

$$X = \sum_{\phi \in \text{ Spec}(\mathcal{A})} e_\phi X,$$

The isotypical component where the isotypical component $e_\phi X = Y_\phi^{m(X,\phi)}$, and where $m(X, \phi)$ is the multiplicity of this component. If we extend our ground field further $Y_\phi \otimes_L K$ may become reducible, but if our extension $L/\mathbb{Q}$ is large enough then Y_ϕ will be absolutely irreducible.

Let us start from a semi simple algebra $\mathcal{A}/\mathbb{Q}$. Then its center $\mathfrak{Z}$ is a direct sum of fields, $\mathfrak{Z} = \oplus \mathfrak{Z}_i$. We say that a finite extension $F/\mathbb{Q}$ is a *splitting field* for

$\mathcal{A}$ if it is normal and if any summand $\mathfrak{Z}_i$ can be embedded into F. Then we get

$$\mathcal{A}_F = \mathcal{A} \otimes_{\mathbb{Q}} F = \bigoplus_{\iota \in \operatorname{Hom}(\mathfrak{Z},F)} \mathcal{A} \otimes_{\mathfrak{Z},\iota} F$$

Clearly the center $\mathcal{A} \otimes_{\mathfrak{Z},\iota} F = F$ and hence we see that this decomposition is the same as the above decomposition (6.28), we get

Proposition 6.3.2. *If $F/\mathbb{Q}$ is a splitting field of $\mathcal{A}/\mathbb{Q}$ the we get an action of the Galois group on Spec$(\mathcal{A}_F)$. The orbits of this actions are in one to one correspondence with the elements in Spec$(\mathcal{A})$ in this is the set of summands of the decomposition of $\mathfrak{Z}_{\mathbb{Q}}$ into a direct sum of fields.*

A summand $\mathcal{A}e_\phi F$ has only one non zero irreducible module (up to isomorphism). This module Y_ϕ is not necessarily absolutely irreducible because $\mathcal{A}e_\phi \xrightarrow{\sim} M_n(\mathcal{D})$ where $\mathcal{D}/F$ may be non trivial (we have a non trivial Schur multiplier).

We say that $\mathcal{A}/\mathbb{Q}$ has trivial Schur multiplier if for all $\phi \in$ Spec$(\mathcal{A})$ the division algebra $\mathcal{D}$ is trivial, i.e. equal to the center.

We apply these general principles to our Hecke -algebra and its action on the cohomology $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$. We define the ideal $I^!_{K_f}$ to be the kernel of this action, then $\mathcal{H}/I^!_{K_f} = \mathcal{A}$ is a finite dimensional algebra. It is known- and will be proved later - that $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ is a semi simple module and hence we see that $\mathcal{A}$ is semi simple. Then we define the scheme

$$\operatorname{Coh}(H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)) = \operatorname{Spec}(\mathcal{A}).$$

We will denote the set of geometric points of this scheme, or more simple minded the set of isomorphism classes occurring in this cohomology, by $\operatorname{Coh}_!(G, K_f, \lambda)$.

More generally we may consider the set of isomorphism classes of absolutely irreducible Hecke modules occurring in the Jordan-Hlder filtration of any of our cohomology modules $H^\bullet_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda))$ and denote this set by $\operatorname{Coh}_?(G, K_f, \lambda)$. Since we have a fixed level K_f they are all defined over a suitable finite extension $F/\mathbb{Q}$.

A central subalgebra

We still consider the action of $\mathcal{H}/I^!_{K_f} = \mathcal{A}$ on $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) = \oplus_q H^q_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$. For all p outside the finite set Σ we have $K_p = \mathcal{G}(\mathbb{Z}_p)$. In this case the algebra $\mathcal{H}_p$ is finitely generated, integral and commutative. We say that $\mathcal{H}_p$ is *unramified* if $K_p = \mathcal{G}(\mathbb{Z}_p)$. For an unramified Hecke-algebra $\mathcal{H}_p$ its maximal spectrum $\operatorname{Hom}_{\text{alg}}(\mathcal{H}_p, \mathbb{C})$,- i.e. the set of isomorphism classes of absolutely irreducible modules over $\mathbb{C}$-,is described by a theorem of Satake which we will recall in the next section.

The subalgebra

$$\mathcal{H}^{(\Sigma)} = \bigotimes_{p \notin \Sigma} \mathcal{H}_p$$

is commutative and its image in $\mathcal{H}/I^!_{K_f}$ lies in the center and hence also in the center of $\mathcal{A}$. Hence we can conclude that for a splitting field F for $\mathcal{A}$ and any irreducible module Y_ϕ for $\mathcal{A}_F$ the restriction of the action to $\mathcal{H}^{(\Sigma)}$ is given by a homomorphism

$$\phi^{(\Sigma)} : \mathcal{H}^{(\Sigma)} \to F.$$

Hence the module Y_ϕ is determined by the action of $\mathcal{H}_\Sigma = \prod_{p\in\Sigma} \mathcal{H}_p$ in $\mathcal{A}_F$. If we assume that Y_ϕ is absolutely irreducible, then it follows from a standard argument that $Y_\phi \xrightarrow{\sim} \otimes_{p\in\Sigma} Y_{\phi_p}$ where Y_{ϕ_p} is an absolutely irreducible $\mathcal{H}_p$-module. For $p \notin \Sigma$ let V_{ϕ_p} be the one dimensional F vector space F with canonical basis element $1 \in F$ and an $\mathcal{H}_p$ action given by the homomorphism $\phi_p : \mathcal{H}_p \to F$. Then we get an isomorphism

$$Y_\phi \xrightarrow{\sim} \bigotimes_p{}' Y_{\phi_p}, \tag{Fl}$$

where we take the restricted tensor product in the usual sense, i.e. at almost all primes the factor in a tensor is equal to 1. Under our assumptions the homomorphism

$$\mathcal{H}_p \to \mathrm{End}_F(Y_{\phi_p})$$

is surjective.

We get a map from the isomorphism classes of irreducible modules $[Y_\phi]$ for $\mathcal{A}_F$ to $\phi^\sigma \in \mathrm{Hom}(\mathcal{H}^{(\Sigma)}, F)$. We say that $\mathcal{H}^{(\Sigma)}$ acts *distinctively* on $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}} \otimes F)$ if this map is injective, i.e. the isomorphism type $[Y_\phi]$ is determined by its restriction to $\mathcal{H}^{(\Sigma)}$.

On the cohomology $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ we still have the action of the group $\pi_0(G(\mathbb{R}))$, this action commutes with the action of the Hecke algebra. (See (6.3.4) This is an elementary abelian 2- group and we may decompose further according to characters $\epsilon : \pi_0(G(\mathbb{R})) \to \{\pm 1\}$.

We say that the $\mathcal{H}$ module $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ has *strong multiplicity one* (with respect to Σ) if $\mathcal{H}^{(\Sigma)}$ acts distinctivly and for any splitting field F and any $\phi^\Sigma : \mathcal{H}^{(\Sigma)} \to F$ we can find a degree q and an ϵ such that

$$H^q_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})(\epsilon) \otimes_{\mathcal{H}^{(\Sigma)}, \phi^{(\Sigma)}} F$$

is an absolutely irreducible $\mathcal{H}-$ module.

If this is so then the homomorphism

$$\mathcal{H}_\Sigma \to \mathrm{End}_F(H^q_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})(\epsilon) \otimes_{\mathcal{H}^{(\Sigma)}, \phi^{(\Sigma)}} F)$$

is surjective and the Hecke module $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ has trivial Schur multiplier.

Representations and Hecke modules

For $p \in \Sigma$ the category of finite dimensional modules is complicated, since the Hecke algebra will not be commutative in general.

Let F be a field of characteristic zero, let V be an F-vector space. An admissible representation of the group $G(\mathbb{Q}_p)$ is an action of $G(\mathbb{Q}_p)$ on V which has the following two properties

(i) For any open compact subgroup $K_p \subset G(\mathbb{Q}_p)$ the space V^{K_p} of K_p invariant vectors is finite dimensional.

(ii) For any vector $v \in V$ we can find an open compact subgroup K_p so that $v \in V^{K_p}$ in other words $V = \lim_{K_p} V^{K_p}$.

Then is is clear that the vector spaces V^{K_p} are modules for the Hecke algebra $\mathcal{H}_{K_p}$. An admissible $G(\mathbb{Q}_p)$ -module V is irreducible if it does not contain an invariant proper submodule. Given such an irreducible module $V \neq (0)$, we can find a K_p such that $V^{K_p} \neq (0)$. We claim that then V^{K_p} is an irreducible $\mathcal{H}_{K_p}$-module. To see this we take the identity element e_{K_p} in our Hecke algebra, it induces a projector on V and a decomposition

$$V = V^{K_p} \oplus V' = e_{K_p} V \oplus (1 - e_{K_p}) V.$$

Let assume we have a proper $\mathcal{H}_{K_p}$-invariant submodule $W \subset V^{K_p}$ Now we convince ourselves that the $G(\mathbb{Q}_p)$-invariant subspace $\tilde{W}$ generated by the elements gw is a proper subspace. We compute the integral

$$\int_{K_p} kgwdk = \int_{K_p \times K_p} k_1 g k_2 w dk_2 dk_1.$$

The first integral gives us the projection to V^{K_p}, the second integral is the Hecke operator, hence the result is in W. We conclude that $e_{K_p}\tilde{W} \subset W$ and tis shows that $(0) \neq \tilde{W} \neq V$.

Now it is not hard to see, that the assignment

$$V \to V^{K_p}$$

from irreducible admissble $G(\mathbb{Q}_p)$-modules with $V^{K_p} \neq (0)$ to finite dimensional irreducible $\mathcal{H}_{K_p}$-modules induces an bijection between the isomorphism classes of the respective types of modules. If we start from V^{K_p} we can reconstruct V by an appropriate form of induction.

The dual module

Let us assume that V is a finite dimensional F-vector space with an action of the Hecke algebra $\mathcal{H}$ (we fix the level). We have an involution on the Hecke algebra which is defined by

$${}^t h(\underline{x}_f) = h(\underline{x}_f^{-1})$$

a simple calculation shows that ${}^t h_1 * {}^t h_2 =^t (h_2 * h_1)$.

This allows us to introduce a Hecke-module structure on $V^\vee = \mathrm{Hom}_F(V, F)$ we for $\phi \in V^\vee$we simply put

$$T_h(\phi)(v) = \phi(T_{{}^t h}(v))$$

for all $v \in V$.

Unitary and essentially unitary representations

Here it seems to be a good moment to recall the notion of unitary Hecke modules and unitary representations. In this book we make the convention that a character is a continuous homomorphism from a topological group $H \to \mathbb{C}^\times$, we do not require that its values have absolute value one. If this is the case we call the character unitary. Our ground field will now be $F=\mathbb{C}$, let V be a $\mathbb{C}$ vector space. We pick a prime p. We call a representation $\rho: G(\mathbb{Q}_p) \to \mathrm{Gl}(V)$ unitary if there is given a positive definite hermitian scalar product $< , > V \times V \to \mathbb{C}$ which is invariant under the action of $G(\mathbb{Q}_p)$.

If our representation is irreducible then it has a central character $\zeta_\rho : C(\mathbb{Q}_p) \to \mathbb{C}^\times$. In this case the scalar product is unique up to a scalar. A necessary condition for the existence of such a scalar product is that $|\zeta_\rho| = 1$, in other words ζ_ρ is unitary.

If this is not the case then our representation may still be *essentially unitary*: We have a unique homomorphism $|\zeta^*_\rho| : C'(\mathbb{Q}_p) \to \mathbb{R}^\times_{>0}$ whose restriction to $C(\mathbb{Q}_p)$ under d_C (see 1.1) is equal to $|\zeta_\rho|$. Then we may form the twisted representation $\rho^* = \rho \otimes |\zeta^*_\rho|^{-1}$. Then the central character of ρ^* is unitary. We say that σ is called essentially unitary if ρ^* is unitary.

If our representation is not irreducible we still can define the notion of being essential unitary. This means that there exists a homomorphism $|\zeta^*_\rho| : C'(\mathbb{Q}_p) \to \mathbb{R}^\times_{>0}$, such that the twisted representation $\rho^* = \rho \otimes |\zeta^*_\rho|^{-1}$ is unitary.

The same notions apply to modules for the Hecke algebra. A (finite dimensional) $\mathbb{C}$ vector space V with an action $\pi_p : \mathcal{H}_p \to \mathrm{End}(V)$ is called unitary, if there is given a positive definite scalar product $< , >: V \times V \to \mathbb{C}$ such that

$$< T_h(v), w > = < v, (T_{{}^t h}(w)). \tag{6.29}$$

Recall that we always assume that our functions $h \in \mathcal{H}_p$ take values in $\mathbb{Q}$, hence we do not need a complex conjugation bar in the expression on the right.

The restriction of π_p to $C(\mathbb{Q}_p)$ in induces a homomorphism $\zeta_{\pi_p} : C(\mathbb{Q}_p) \to \mathbb{C}^\times$. We call π_p isobaric if this action of the center is semi simple - and therefore a direct sum of characters $\zeta_{\pi_p} = \sum \zeta^\nu_{\pi_p}$ - and if all these characters have the same absolute values $|\zeta^\nu_{\pi_p}| = |\zeta_{\pi_p}|$. This means that we can find $|\zeta^*_{\pi_p}|$ as above. Then we call π_p essentially unitary if the Hecke module $\pi^*_p = \pi_p \otimes |\zeta^*_{\pi_p}|^{-1}$ is unitary.

These boring considerations will be needed later, we will see that for an irreducible coefficient system $\mathcal{M}$ the $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) \otimes \mathbb{C}$ is essentially unitary (see 8.1.5).

Satake's theorem

In the formulation of this theorem I will use the language of group schemes, the reader not so familiar with this language may think of Gl_n or the group of symplectic similitudes GSp_n. Since we assumed that for $p \notin \Sigma$ the integral structure $\mathbb{G}/\mathrm{Spec}(\mathbb{Z}_p)$ is reductive it is also quasisplit. We can find a Borel subgroup $\mathcal{B}/\mathrm{Spec}(\mathbb{Z}_p) \subset \mathbb{G}/\mathrm{Spec}(\mathbb{Z}_p)$ and a maximal torus $\mathcal{T}/\mathrm{Spec}(\mathbb{Z}_p) \subset \mathcal{B}/\mathrm{Spec}(\mathbb{Z}_p)$. Then our torus $\mathcal{T}/\mathrm{Spec}(\mathbb{Z}_p)$ splits over an unramified extension $E_p/\mathbb{Q}_p$ and the Galois group $\mathrm{Gal}(E_p/\mathbb{Q}_p)$ acts on the character module $X^*(\mathcal{T} \times E_p) = \mathrm{Hom}(\mathcal{T} \times E_p, \mathbb{G}_m)$. Let $\{\alpha_1, \alpha_2, \ldots, \alpha_r\} \subset X^*(\mathcal{T} \times E_p)$ be the set of positive simple roots, it is invariant under the action of the Galois group. Let $W(\mathbb{Z}_p)$ be the centralizer of the Galois action in the absolute Weyl group W. We introduce the module of unramified characters on the torus this is

$$\mathrm{Hom}_{\mathrm{unram}}(\mathcal{T}(\mathbb{Q}_p),\mathbb{C}^\times) = \mathrm{Hom}(\mathcal{T}(\mathbb{Q}_p)/\mathcal{T}(\mathbb{Z}_p),\mathbb{C}^\times) = \Lambda(\mathcal{T}).$$

We also view $\omega_p \in \Lambda(\mathcal{T})$ as a character $\omega_p : B(\mathbb{Q}_p) \to \mathbb{C}^\times,\ \lambda \mapsto \lambda(b) = b^{\omega_p}$. The group of characters $\mathrm{Hom}(\mathcal{T},\mathbb{G}_m) = X^*(T)^{\,\mathrm{Gal}(E_p/\mathbb{Q}_p)}$ is a subgroup of $\Lambda(T)$: An element $\gamma \in X^*(\mathcal{T})^{\,\mathrm{Gal}(E_p/\mathbb{Q}_p)}$ defines a homomorphism $\mathcal{T}(\mathbb{Q}_p) \to \mathbb{Q}_p^\times$ and this gives us the following element $x \mapsto |\gamma(x)|_p \in \Lambda(\mathcal{T})$ which we denote by $|\gamma|$. We can even do this for elements $\gamma \otimes \frac{1}{n} \in X^*(T)\otimes\mathbb{Q}$, then $\gamma\otimes\frac{1}{n}(x) = |\gamma(x)|_p^{1/n} \in \mathbb{R}_{>0}^\times$. Our open compact subgroup $K_p = \mathbb{G}(\mathbb{Z}_p)$. Since we have the Iwasawa decomposition $G(\mathbb{Q}_p) = B(\mathbb{Q}_p)\mathbb{G}(\mathbb{Z}_p) = B(\mathbb{Q}_p)K_p$ we can attach to any $\omega_p \in \Lambda(\mathcal{T})$ a *spherical function*

$$\phi_{\omega_p}(g) = \phi_{\omega_p}(b_pk_p) = (\omega_p + |\rho|_p)(b_p) \tag{6.30}$$

here $\rho \in \Lambda(\mathcal{T})\otimes\mathbb{Q}$ is the half sum of positive roots. This spherical function is of course an eigenfunction for $\mathcal{H}_p$ under convolution, i.e. for $h_p \in \mathcal{H}_p$

$$\int_{G(\mathbb{Q}_p)} \phi_{\omega_p}(gx)h_p(x)dx = \hat{h}_p(\omega_p)\phi_{\omega_p}(g) \tag{6.31}$$

and $\mathfrak{s}(\omega_p) : h_p \mapsto \hat{h}_p(\omega_p)$ is an algebra homomorphism from $\mathcal{H}_p$ to $\mathbb{C}$. Of course the measure dx gives volume 1 to $\mathbb{G}(\mathbb{Z}_p) = K_p$.

The theorem of Satake asserts:

Theorem 6.3.1. *The group $W(\mathbb{Z}_p)$ acts on $\Lambda(\mathcal{T})$, we have $\mathfrak{s}(w\omega_p)) = \mathfrak{s}(\omega_p)$ and*

$$\Lambda(\mathcal{T})/W(\mathbb{Q}_p) \xrightarrow{\mathfrak{s}} Hom_{\mathrm{alg}}(\mathcal{H}_p,\mathbb{C})$$

is an isomophism.

We will write irreducible modules in this case as $\pi_p = \pi_p(\omega_p)$ and $\omega_p \in \Lambda(\mathcal{T})/W(\mathbb{Q}_p)$ is the so called *Satake parameter* of π_p.

The Hecke algebra is generated by the characteristic functions of double cosets $K_pt_pK_p$ where $t_p \in T(\mathbb{Q}_p)$ and where for all simple roots $\alpha \in \pi$ we have $|\alpha(t_p)|_p \le 1$, i.e. $t_p \in T_+(\mathbb{Q}_p)$. Then the evaluation in (6.31) comes down to the computation the integrals

$$\int_{K_pt_pK_p} \phi_{\omega_p}(gx)dx = \hat{t}_p(\omega_p)\phi_{\omega_p}(g) \tag{6.32}$$

We discuss this evaluation in (7.0.6)

Spherical representations

Now we assume that Let $F' \subset \mathbb{C}$ be a finite extension of $\mathbb{Q}$ and let V/F be a vector space. We choose $K_p = \mathbb{G}(\mathbb{Z}_p)$, i.e. p is unramified. An admissible representation

$$\tilde{\pi}_p : G(\mathbb{Q}_p) \to \mathrm{Gl}(V)$$

is called *spherical* if $V^{K_p} \neq 0$, and this space is a module for the Hecke algebra. If the representation is absolutely irreducible, then it is well known that $\dim_{F'} V^{K_p} = 1$, this is a one dimensional module for $\mathcal{H}_{K_p}$, i.e. a homomorphism $\pi_p : \mathcal{H}_{K_p} \to F'$. Let $\omega_p \in \Lambda(\mathcal{T})$ the corresponding Satake parameter, it is well defined modulo the action of the group $W(\mathbb{Q}_p)$. We consider the field F' which is generated by the values $\hat{t}_p(\omega_p)$. Then the one dimensional F' vector space

$$H_{\pi_p} = F'\phi_{\omega_p} \tag{6.33}$$

will be our standard model for the isomorphism type π_p.

The representation $\tilde{\pi}_p$ can be realized as a submodule J_{π_p} of the induced representation

$$H_{\tilde{\pi}_p} = \ \mathrm{Ind}_{B(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)} F'\phi_{\omega_p} = \{f : G(\mathbb{Q}_p) \to F' | f(bg) = \omega_p(b)|\rho|_p(b)f(g)\}$$

where f satisfies the (obvious) condition that there exists a finite index subgroup $K'_p \subset K_p$ such that f is invariant under right translations by elements $k' \in K'_p$. In general this module $H_{\tilde{\pi}_p}$ will be irreducible and then $J_{\pi_p} = H_{\tilde{\pi}_p}$.

If $\tilde{\pi}_p^{\vee}$ is the spherical representation attached to the Satake parameter ω_p^{-1} then we have a pairing

$$\begin{gathered} H_{\tilde{\pi}_p} \times H_{\tilde{\pi}_p^{\vee}} \to \mathbb{C} \\ f_1 \times f_2 \mapsto \textstyle\int_{K_p} f_1(k_p) f_2(k_p) dk_p \end{gathered} \tag{6.34}$$

This tells us that the dual module to $H_{\pi_p} = H_{\tilde{\pi}_p}^{K_p}$ has the Satake parameter ω_p^{-1}. The representations $H_{\tilde{\pi}_p}$ are called the representations of the unramified principal series.

We may consider the case that ω_p is a unitary character, this means that $\omega_p : \mathcal{T}(\mathbb{Q}_p)/\mathcal{T}(\mathbb{Z}_p) \to \mathbb{S}^1$. Then we have $\omega_p^{-1}(t) = \overline{\omega_p}(t)$ and our above pairing defines a positive definite hermitian scalar product

$$< \, , \, >: H_{\tilde{\pi}_p} \times H_{\tilde{\pi}_p} \to \mathbb{C} \tag{6.35}$$

which is given by

$$< f_1, f_2 >= \int_{K_p} f_1(k_p) \overline{f_2(k_p)} dk_p \tag{6.36}$$

If we allow for $f \in H_{\tilde{\pi}_p}$ all the functions whose restriction to K_p lies in $L^2(K_p)$ then $H_{\tilde{\pi}_p}$ becomes a Hilbert space and the representation of $G(\mathbb{Q}_p)$ on $H_{\tilde{\pi}_p}$ is a unitary representation.

These representations are called the unitary principal series representations. It is not the case that these representations are the only unramified principal series representations which carry an invariant positive definite scalar product. (See [Sat]).

In the following section we discuss the classical case.

The case Gl_2.

In the case of Gl_2 the maximal torus is given by

$$T(\mathbb{Q}_p) = \left\{ \begin{pmatrix} t_1 & 0 \\ 0 & t_2 \end{pmatrix} \right\}.$$

It is contained in the two Borel subgroups $B/\mathbb{Q}$ of upper and $B_-/\mathbb{Q}$ of lower triangular matrices. Let $U/\mathbb{Q}$ be the unipotent radical of B.

If we represent an element $\bar{\omega}_p \in \Lambda(\mathcal{T})/W$ by $\omega_p : T(\mathbb{Q}_p)/T(\mathbb{Z}_p) \to \mathbb{C}^\times$ then we get two numbers

$$\begin{array}{c} \omega_p(\begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix}) = \alpha'_p \\ \omega_p(\begin{pmatrix} 1 & 0 \\ 0 & p \end{pmatrix}) = \beta'_p \end{array}.$$

The local algebra is generated by two operators $T_p, T(p,p)$ for which

$$\begin{array}{c} \mathfrak{s}(\bar{\omega}_p)(T_p) = p^{1/2}(\alpha'_p + \beta'_p) = \alpha_p + \beta_p \\ \mathfrak{s}(\bar{\omega}_p)(T(p,p)) = p\alpha'_p\beta'_p = \alpha_p\beta_p \end{array}.$$

These two Hecke operators are -up to a normalizing factor - defined as the characteristic functions of the double cosets

$$\mathrm{Gl}_2(\mathbb{Z}_p) \begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix} \mathrm{Gl}_2(\mathbb{Z}_p) \text{ and } \mathrm{Gl}_2(\mathbb{Z}_p) \begin{pmatrix} p & 0 \\ 0 & p \end{pmatrix} \mathrm{Gl}_2(\mathbb{Z}_p).$$

The to numbers $\alpha_p + \beta_p, \alpha_p\beta_p$ determine ω_p. They are also called the Satake parameters.

It is not difficult to prove Satakes theorem for $\mathrm{Gl}_2/\mathbb{Q}_p$. We write $\mathrm{Gl}_2(\mathbb{Z}_p) = K_p$. It is the theorem for elementary divisors that all the double cosets $K_p\backslash G(\mathbb{Q}_p)/K_p$ are of the form

$$K_p \begin{pmatrix} p^a & 0 \\ 0 & p^b \end{pmatrix} K_p \text{ with } a \geq b.$$

If we want to understand the function $h \mapsto \hat{h}(\lambda)$ it clearly suffices to compute its value on the characteristic function t_{p^m} of the double coset

$$K_p \begin{pmatrix} p^m & 0 \\ 0 & 1 \end{pmatrix} K_p$$

To do this we have to evaluate the integral

$$\int_{G(\mathbb{Q}_p)} \phi_\lambda(x) t_{p^m}(x) dx = \hat{t_{p^m}}(\lambda).$$

We abbreviate $y_p = \begin{pmatrix} p^m & 0 \\ 0 & 1 \end{pmatrix}$ and write our double coset as a union of right K_p cosets, i.e.

$$K_p y_p K_p = \bigcup_{\xi \in K_p/K_p \cap y_p K_p y_p^{-1}} \xi y_p K_p.$$

The volume of such a coset is one hence we get

$$\int_{G(\mathbb{Q}_p)} \phi_\lambda(x) t_{p^m}(x) dx = \sum_\xi \phi_\lambda(\xi y_p)$$

The group

$$K_p \cap y_p K_p y_p^{-1} = \{\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in K_p | b \equiv 0 \mod p^m\},$$

this is the group of points $B_-(\mathbb{Z}/p^m)$ of lower triangular matrices. Hence the coset space

$$\mathrm{Gl}_2(\mathbb{Z}/p^m)/B_-(\mathbb{Z}/p^m) = K_p/K_p \cap y_p K_p y_p^{-1} = \mathbb{P}^1(\mathbb{Z}/p^m).$$

The points in $\mathbb{P}^1(\mathbb{Z}/p^m)$ are arrays $\begin{pmatrix} a \\ b \end{pmatrix}$, $a, b \in \mathbb{Z}/p^m, a$ or $b \in (\mathbb{Z}/p^m\mathbb{Z})^\times$, modulo $(\mathbb{Z}/p^m)^\times$. Then K_p acts by multiplication from the left on this coset space and $K_p \cap y_p K_p y_p^{-1}$ is the stablizer of $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$. We still have an action of $B(\mathbb{Z}/p^m)$ from the left on $\mathbb{P}^1(\mathbb{Z}/p^m)$ and the orbits under this action from the left can be represented by

$$\begin{pmatrix} 0 \\ 1 \end{pmatrix} \text{ and } \begin{pmatrix} 1 \\ p^\nu \end{pmatrix} \text{ for } \nu = 1, \dots m$$

On these orbits the function $\xi \mapsto \phi_\lambda(\xi y_p)$ is constant. We can take the representatives

$$\xi = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \text{ and } \begin{pmatrix} 0 & 1 \\ -1 & p^\nu \end{pmatrix}$$

and get the values

$$\phi_\lambda(y_p) = p^{-m}\alpha_p^m$$

$$\phi_\lambda(\begin{pmatrix} 0 & 1 \\ -p^m & p^\nu \end{pmatrix}) = \phi_\lambda(\begin{pmatrix} p^{m-\nu} & * \\ 0 & p^\nu \end{pmatrix} k_p) = \alpha_p^{m-\nu}\beta_p^\nu p^{\nu-m}.$$

The length of these orbits is $p^m, \{p^{m-\nu}(1-\frac{1}{p})\}_{\nu=1,\dots,m-1}, 1$, and we get

$$\hat{t_{p^m}}(\lambda) = \alpha_p^m + \beta_p^m + (1-\frac{1}{p}) \sum_{\nu=1}^{m-1} \alpha_p^{m-\nu}\beta_p^\nu.$$

This formula clearly proves the theorem of Satake in this special case.

A very specific case

We consider the case

6.3.4 Back to cohomology

The case of a torus and the central character

We consider the case that our group $G/\mathbb{Q}$ is a torus $T/\mathbb{Q}$. This case is already discussed in [Ha-Gl2]. Our torus splits over a finite extension $F/\mathbb{Q}$ and our absolutely irreducible representation is simply a character $\gamma : T \times_{\mathbb{Q}} F \to \mathbb{G}_m$, it defines a one dimensional $T \times_{\mathbb{Q}} F-$ module $F[\gamma]$. Here $F[\gamma]$ is simply the one dimensional vector space F over F with $T \times_{\mathbb{Q}} F$ acting by the character γ.

We recall the notion of an algebraic Hecke character of type γ. We choose an embedding $\iota : F \hookrightarrow \bar{\mathbb{Q}}$ then γ induces a homomorphisms $T(\mathbb{C}) \to \mathbb{C}^\times$. The restriction of this homomorphism to $T(\mathbb{R})$ is called $\gamma_\infty : T(\mathbb{R}) \to \mathbb{C}^\times$.

A continuos homomorphism

$$\phi = \phi_\infty \times \Pi_p \phi_p = \phi_\infty \times \phi_f \ : T(\mathbb{A})/T(\mathbb{Q}) \to \mathbb{C}^\times$$

is called an *algebraic Hecke character of type* γ if the restrictions to the connected component of the identity satisfy

$$\phi_\infty|_{T^{(0)}(\mathbb{R})} = \gamma_\infty^{-1}|_{T^{(0)}(\mathbb{R})}.$$

The finite part $\phi_f : T(\mathbb{A}_f) \to \bar{\mathbb{Q}}^\times$ is trivial on some open compact subgroup $K_f^T \subset T(\mathbb{A}_f)$. We also say that a homomorphism $\phi_1 : T(\mathbb{A}_f)/K_f^T \to \bar{\mathbb{Q}}^\times$ is an algebraic Hecke-character, if it is the finite part of an algebraic Hecke character, which is then uniquely defined.

In [Ha-Gl2], 2.5.5 we explain that the cohomology vanishes (for any choice of K_f^C) if γ is not the type of an algebraic Hecke character. In this case we give the complete description of the cohomology in [Ha-Gl2], 2.6: If we choose $Z' = Z$ (see 1.1) then

$$H^0(S^C_{K_f^C}, F[\gamma] \otimes_{F,\iota} \otimes \bar{\mathbb{Q}}) = \bigoplus_{\phi_f : C(\mathbb{A}_f)/K_f^C) \to \bar{\mathbb{Q}}^\times : \mathrm{type}(\phi_f) = \gamma} \bar{\mathbb{Q}}\phi_f. \tag{6.37}$$

The property of γ to be the type of an algebraic Hecke character does not depend on the choice of ι. If we fix the level then it is easy to see that the values of the characters ϕ_f lie in a finite extension F_1 of $\iota(F)$ so we may replace in our formula above the algebraic closure $\mathbb{Q}$ by F_1.

If we return to our group $G/\mathbb{Q}$ and if we start from an absolutely irreducible representation $G \times_{\mathbb{Q}} F \to \mathrm{Gl}(\mathcal{M})$ then its restriction to the center $C/\mathbb{Q}$ is a character $\zeta_{\mathcal{M}}$. Our remark above implies that this character must be the type of an algebraic Hecke character if we want the cohomology $H^\bullet_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ to be non trivial. (Look at a suitable spectral sequence).

In any case we can consider the sub algebra $C_{K_f} \subset \mathcal{H}_{K_f}$ generated by central double cosets $K_f \underline{z}_f K_f = K_f \underline{z}_f$. with $\underline{z}_f \in C(\mathbb{A}_f)$ This provides an action of the group $C(\mathbb{A}_f)/K_f^C$ on the cohomology $H^\bullet_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$. Then the following proposition is obvious

Proposition 6.3.3. *Let H_{π_f} be an absolutely irreducible subquotient in the Jordan Hölder series in any of our cohomology groups. Then $C(\mathbb{A}_f)/K_f^C$ acts by a character ζ_{π_f} on H_{π_f} and ζ_{π_f} is an algebraic Hecke character of type $\zeta_{\mathcal{M}}$.*

Note that $\zeta_{\mathcal{M}}$ is the restriction of the abelian component δ in $\lambda = \lambda^{(1)} + \delta$ to the center.

The cohomology in degree zero

Let us start from an absolutely irreducible representation $r : G \times F \to \mathrm{Gl}(\mathcal{M})$, we want to understand $H^0(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$: To do this we have to understand the connected components of the space and the spaces of invariants in $\tilde{\mathcal{M}}$ under the discrete subgroups $\Gamma^{\underline{g}_f}$ in 1.2.1. We assume that the groups $\Gamma^{\underline{g}_f} \cap G^{(1)}(\mathbb{Q})$ are Zariski dense in $G^{(1)}$. Then it is clear that we can have non trivial cohomology in degree zero if $\mathcal{M}$ is one dimensional and $G^{(1)}$ acts trivially. Hence $\mathcal{M}$ is given by a character $\delta : C' \times F \to \mathbb{G}_m \times F$.

To simplify the situation we assume that the assumptions in (6.1.3) are fulfilled and we have a bijection

$$\pi_0(\mathcal{S}^G_{K_f}) \xrightarrow{\sim} \pi_0(\mathcal{S}^{C'}_{K^{C'}_\infty \times K^{C'}_f}) \tag{6.38}$$

where $K^{C'}_\infty$ and $K^{C'}_f$ are the images of the chosen compact subgroups respectively. With these data we define $\mathcal{S}^{C'}_{K^{C'}_f}$ and we can view $\mathcal{M}$ as a sheaf on $\mathcal{S}^{C'}_{K^{C'}_f}$, in our previous notation it is the sheaf $\tilde{F}[\delta]$.

Then we get for an absolutely irreducible $G \times F$ module $\mathcal{M}$ -and under the assumption that the $\Gamma^{\underline{g}_f} \cap G^{(1)}(\mathbb{Q})$ are Zariski dense in $G^{(1)}$- that (See 6.3.4)

$$H^0(\mathcal{S}^G_{K_f}, \mathcal{M} \otimes F_1) = \begin{cases} 0 & \text{if } \dim(\mathcal{M}) > 1 \\ \bigoplus_{\phi_f : \mathrm{type}(\phi_f) = \delta} F_1 \phi & \text{if } \mathcal{M} = F[\delta] \end{cases} \tag{6.39}$$

The density assumption is fulfilled if $G^{(1)}/\mathbb{Q}$ is quasisplit. We also observe that we have the isogeny $d_C : C \to C'$ (See (1.1). Then it is clear that the composition $d_C \circ \delta$ is the character $\zeta_{\mathcal{M}}$ in section 6.3.4.

The Manin-Drinfeld principle

For a moment we assume that our coefficient systems are rational vector spaces. This means that we start from a rational (preferably absolutely irreducible) representation $\rho : G \times_{\mathbb{Q}} F_0 \to \mathrm{Gl}(\mathcal{M})$ where $\mathcal{M}$ is a finite dimensional F_0 vector spaces. We have an action of $\mathcal{H}_{F_0}$ on our cohomology groups and we defined the spectra $\mathrm{Coh}(H^\bullet_?(\mathcal{S}^G_{K_f}, \mathcal{M}))$ which now will be a finite scheme over F_0. We will show show that the modules $H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_L)$ are semi simple and if we pass to a splitting field F/F_0 we can decompose

$$H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})(\Pi_f) \otimes F = \bigoplus_{\pi_f} H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})(\pi_f) = \bigoplus_{\pi_f} e_{\pi_f} H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) \tag{6.40}$$

Here we changed our notation slightly, we replaced the ϕ by π_f. The isomorphism types π_f are not necessarily absolutely irreducible, but if we extend our field further then they decompose in a direct sum of modules of exactly one isomorphism type. We call the above decomposition the isotypical decomposition and under our assumption on F the summands are absolutely isotypical.

We say that for a cohomology group $H^i(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F)$ (resp. $H^\bullet_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F)$ satisfies the *Manin-Drinfeld principle*, if $\mathrm{Coh}(H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F) \cap \mathrm{Coh}(H^i(\partial(\mathcal{S}^G_{K_f}), \tilde{\mathcal{M}}_F) = \emptyset$ (resp $\mathrm{Coh}(H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F) \cap \mathrm{Coh}(H^{i-1}(\partial(\mathcal{S}^G_{K_f}), \tilde{\mathcal{M}}_F) = \emptyset$.

We have defined $\mathrm{Coh}(X)(=\ \mathrm{Spec}(\mathcal{H}/I(X)))$ for any Hecke-module X and if X is a submodule of another Hecke module Y then we say that X satisfies the Manin-Drinfeld principle with respect to Y if $\mathrm{Coh}(X)\cap\mathrm{Coh}(Y/X)=\emptyset$.

If the Manin-Drinfeld principle is valid we get canonical decompositions

$$H^i(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)=\ \mathrm{Im}(H^i(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)\longrightarrow H^i(\partial(\mathcal{S}^G_{K_f}),\tilde{\mathcal{M}}_F))\oplus H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F), \tag{6.41}$$

$$H^i_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)=\ \mathrm{Im}(H^{i-1}(\partial\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)\longrightarrow H^i_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F))\oplus H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F),$$

which is invariant under the action of the Hecke algebra and no irreducible representation $\overline{\pi}_\infty\times\pi_f$ which occurs in $H^i_!(\mathcal{S}^G_{K_f},\mathcal{M}_F)$ can occur as a sub quotient in $\mathrm{Im}(H^{i-1}(\partial\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)\to H^i_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F))$.

In the second case we will call the above image of the boundary cohomology the Eisenstein subspace or compactly supported Eisenstein cohomology and denote it by

$$\mathrm{Im}(H^{i-1}(\partial\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)\longrightarrow H^i_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}))=H^i_{c,\ \mathrm{Eis}}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}).$$

In the first case we can consider the module $H^i_{\mathrm{Eis}}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)\subset\ \mathrm{Im}(H^i(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)\longrightarrow H^i(\partial(\mathcal{S}^G_{K_f}),\tilde{\mathcal{M}}_F))$ as a submodule in $H^i(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)$ and this submodule is called the Eisenstein cohomology. Under the assumption of the Manin-Drinfeld principle we have a canonical section $s: H^i_{\mathrm{Eis}}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)\to H^i\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)$.

If we know the Manin-Drinfeld principle we can ask new questions. We return to the the integral cohomology $H^i_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F})$ and map it into the rational cohomology then the image is called $H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})_{\ \mathrm{int}}\subset H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)$ this is also the module which we get if we divide $H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F})))$ by the torsion. (This may be not true for $?=!$)

Our decompositions above do not induce decomposition on the groups $H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})_{\ \mathrm{int}}$. Whenever we have a decomposition $H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)=X\oplus Y$ we can take the intersections $X_{\mathrm{int}}\cap H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})_{\ \mathrm{int}}$ and the same for Y and get a decomposition *up to isogeny*

$$X_{\mathrm{int}}\oplus Y_{\mathrm{int}}\subset H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})_{\ \mathrm{int}},$$

where up to isogeny means that the left hand side is of finite index in the right hand side.

For instance the Manin-Drinfeld decomposition above yields (if it exists) a decomposition up to isogeny

$$H^i_{c,\ \mathrm{Eis}}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})_{\ \mathrm{int}}\oplus H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})_{\ \mathrm{int}}\subset H^i_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})_{\ \mathrm{int}},$$

it is canonical but the direct sum is only of finite index in the right hand side module. The primes dividing the order of the index are called *Eisenstein primes.*

These Eisenstein primes have been studied in the case $G=\mathrm{Gl}_2/\mathbb{Q}$ but they also seem to play a role in more general situation. The general philosophy is that they are related to the arithmetic of special values of L-functions. (See [Ha-Cong])

The same applies to the decomposition of $H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})_{\text{ int}}$ in isotypical summands. We put

$$H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})(\pi_f)\cap H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}} = H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}}(\pi_f).$$

Then we get an decomposition up to isogeny

$$\bigoplus_{\pi_f} H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}}(\pi_f)\subset H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}}. \tag{6.42}$$

It is a very interesting question to learn something about the the structure of the quotient of the right hand side by the left hand side. The structure of this quotient should be related to the arithmetic of special values of L-functions. (See [Hi]).

The action of $\pi_0(G(\mathbb{R}))$

We have seen that we can choose a maximal torus $T/\mathbb{Q}$ such that $T(\mathbb{R})[2]$ normalizes K_∞. We know that $T(\mathbb{R})[2]\to\pi_0(G(\mathbb{R}))$ is surjective and that $T(\mathbb{R})[2]\cap G^{(1)}(\mathbb{R})\subset K_\infty$. This allows us to define an action of $\pi_0(G(\mathbb{R}))$ on the various cohomology groups and this action commutes with the action of the Hecke-algebra. Therefore we can decompose any isotypical subspace in a cohomology group into eigenspaces under this action

$$H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)(\pi_f)=\bigoplus_{\epsilon_\infty} H^\bullet_?(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)(\pi_f\times\epsilon_\infty) \tag{6.43}$$

and for the integral lattices we get a decomposition up to isogeny

$$\bigoplus_{\pi_f\times\epsilon_\infty} H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}}(\pi_f\times\epsilon_\infty)\subset H^i_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}} \tag{6.44}$$

6.3.5 Some questions and and some simple facts

Of course we can be more modest and we may only ask for the dimension of the cohomology groups $H^i(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})$, this question will be discussed later in Chapter V and can be answered in some simple cases.

If we are a little bit more modest we can ask for the Euler characteristic

$$\chi(H^\bullet(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})=\sum_i(-1)^i\dim(H^i(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}))$$

This question can be answered in a certain sense. If the subgroup K_f is neat (See 1.1.2.1) , then $\mathcal{S}^G_{K_f}$ is a disjoint union of locally symmetric spaces. On these spaces exists a differential form of highest degree, which is obtained from differential geometric data, this is the Gauss-Bonnet form ω^{GB}. Then the Gauss-Bonnet theorem yields that

$$\chi(H^\bullet(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})=\dim(\mathcal{M}))\int_{\mathcal{S}^G_{K_f}}\omega^{GB}.$$

This will be discussed in more detail in Chap V. This implies of course, that for a covering $\mathcal{S}^G_{K'_f} \to \mathcal{S}^G_{K_f}$, where $K'_f \subset K_f$ and both groups are neat,we get

$$\chi(\mathcal{S}^G_{K'_f}, \tilde{\mathcal{M}}) = \chi(H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})[K'_f : K_f],$$

a fact which also follows easily from topological considerations.

This leads us-following C.T.C. Wall- to introduce the orbifold Euler characteristic for a not necessarily neat K_f by

$$\chi_{\mathrm{orb}}(H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})) = \frac{1}{[K'_f : K_f]}\chi(\mathcal{S}^G_{K'_f}, \tilde{\mathcal{M}})$$

where $K'_f \subset K_f$ is a neat subgroup of finite index. The orbifold Euler characteristic may differ from the Euler characteristic $\chi(H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ by a sum of contributions coming from the set of fixed points of the Γ_i on X (See 1.1.2.1).

This is perhaps the right moment, to discuss another minor technical point. When we discuss the action of the Hecke algebra $\mathcal{H}_{K_f} = \mathcal{C}_c(G(\mathbb{A}_f)//K_f, \mathbb{Q})$ on $H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ then we chose the same K_f for the space and for the Hecke algebra. We also normalized the measure on the group so that it gave volume 1 to K_f. But we have of course an inclusion of Hecke algebras $\mathcal{H}_{K_f} \subset \mathcal{H}_{K'_f}$. Therefore $\mathcal{H}_{K_f}$ also acts on $H^\bullet(\mathcal{S}^G_{K'_f}, \tilde{\mathcal{M}})$. This contains $H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ but then the inclusion is not compatible with the action of the Hecke algebra. We therefore choose a measure independently of the level, if we are in a situation where we vary the level. In such a case a measure provided by an invariant form ω_G on G (See 2.1.3) is a good choice. If we now define the action of the Hecke operators by means of this measure. With this choice of a measure the inclusion $\mathcal{H}_{K_f} \subset \mathcal{H}_{K'_f}$ is compatible with the inclusion of the cohomology groups.

Then we see the the new Hecke operator $T_h^{(\omega_G)}$, and the old one are related by the formula

$$T_h = \frac{1}{\mathrm{vol}_{|\omega_G|}(K_f)} T_h^{(\omega_G)}$$

The reader might raise the question, why we work with fixed levels and why we do not pass to the limit. The reason is that for some questions we need to work with the integral cohomology, and this does not behave so well under change of level.

Homology

We may also define homology groups $H_i(\mathcal{S}^G_{K_f}, \underline{\mathcal{M}}_\lambda)$ and $H_i(\mathcal{S}^G_{K_f}, \partial\mathcal{S}^G_{K_f}, \underline{\mathcal{M}}_\lambda)$, here $\mathcal{M}_\lambda$ is a "cosheaf". The "costalk" $\underline{\mathcal{M}}_{\mathbb{Z},x}$ is obtained as follows: We consider $\pi^{-1}(x)$ and

$$\bigoplus_{\underline{y}=y\times \underline{g}_f K_f/K_f} \underline{g}_f \mathcal{M}_\lambda,$$

and the action of $G(\mathbb{Q})$ on this direct sum. Then $\underline{\mathcal{M}}_{\lambda,x}$ is the module of coinvariants. If we pick a point $\underline{y} = y \times \underline{g}_f K_f/K_f$, which maps to $x \in \mathcal{S}^G_{K_f}$ then we get an isomorphism

$$\underline{\mathcal{M}}_{\lambda,x} \simeq (g_f\mathcal{M}_\lambda)_{\Gamma_{\underline{y}}^{(\underline{g}_f)}}.$$

We define the chain complex

$$C_i(\mathcal{S}^G_{K_f}, \underline{\mathcal{M}}_\lambda)$$

and the above homology groups are given by the homology of this complex.

If we assume that $\mathcal{S}^G_{K_f}$ is oriented (ref. to prop 1.3) then we know (Chap. II 2. 1. 5) that we have isomorphisms which are compatible with the fundamental exact sequence

$$\begin{array}{ccc}
\downarrow & & \downarrow \\
H^{i-1}(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) & \xrightarrow{\sim} & H_{d-i}(\partial\mathcal{S}^G_{K_f}, \underline{\mathcal{M}}_\lambda) \\
\downarrow & & \downarrow \\
H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) & \xrightarrow{\sim} & H_{d-i}(\mathcal{S}^G_{K_f}, \underline{\mathcal{M}}_\lambda) \\
\downarrow & & \downarrow \\
H^i(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) & \xrightarrow{\sim} & H_{d-i}(\mathcal{S}^G_{K_f}, \partial\mathcal{S}^G_{K_f}, \underline{\mathcal{M}}_\lambda) \\
\downarrow & & \downarrow \\
H^i(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) & \xrightarrow{\sim} & H_{d-i-1}(\partial\mathcal{S}^G_{K_f}, \underline{\mathcal{M}}_\lambda) \\
\downarrow & & \downarrow
\end{array}$$

Poincaré duality

We assume that $\mathcal{S}^G_{K_f}$ is connected. If we denote the dual representation by $\mathcal{M}^\vee_\lambda = \mathcal{M}_{w_0(\lambda)}$ (we choose a suitable lattice lattice $\mathcal{M}^\vee_\mathbb{Z}$then we have the canonical homomorphism $\mathcal{M}_\lambda \otimes \mathcal{M}^\vee_\lambda \to \mathbb{Z}$ and the standard pairing between the homology and the cohomology groups yields pairings

$$\begin{array}{ccccc}
H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \times H_i(\mathcal{S}^G_{K_f}, \partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}^\vee_\lambda) & \to & H^0(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \tilde{\mathcal{M}}^\vee_\lambda) & \to & H^0(\mathcal{S}^G_{K_f}, \mathbb{Z}) \\
\downarrow \qquad\qquad \uparrow & & \downarrow & & \downarrow \\
H^i(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \times H_i(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee}) & \to & H^0(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \tilde{\mathcal{M}}^\vee_\lambda) & \to & H^0(\mathcal{S}^G_{K_f}, \mathbb{Z})
\end{array}$$

This pairing is of course compatible with the isomorphism between homology and cohomology and then the pairing becomes the cup product. We get the diagram

$$\begin{array}{ccccc}
H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \times H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}^\vee_\lambda) & \to & H^d_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \tilde{\mathcal{M}}^\vee_\lambda) & \to & H^d_c(\mathcal{S}^G_{K_f}, \mathbb{Z}) \\
\downarrow \qquad\qquad \uparrow & & \downarrow & & \downarrow \\
H^i(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \times H^{d-i}_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee}) & \to & H^d_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \tilde{\mathcal{M}}^\vee_\lambda) & \to & H^d_c(\mathcal{S}^G_{K_f}, \mathbb{Z})
\end{array}$$

We know that the manifold with corners $\partial\mathcal{S}^G_{K_f}$ "smoothable" it can be approximated by a $\mathcal{C}-$ manifold and therefore we also have a pairing $<\,,\,>_\partial$ on the cohomology of the boundary. This pairing is consistent with the fundamental long exact sequence (Thm. 6.2.1). We write this sequence twice but the second time in the opposite direction and the pairing $<\,,\,>$ in vertical direction:

$$\begin{array}{cccccc}
\to & H^p(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) & \xrightarrow{r} & H^p(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) & \xrightarrow{\delta} \\
 & \times & & \times & \\
\leftarrow & H^{d-p}_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee}) & \xleftarrow{\delta} & H^{d-p-1}(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee}) & \leftarrow \\
 & \downarrow <\,,\,> & & \downarrow <\,,\,>_\partial & \\
 & H^d_c(\mathcal{S}^G_{K_f}, \mathbb{Z}) & \xleftarrow{\delta_d} & H^{d-1}_c(\partial\mathcal{S}^G_{K_f}, \mathbb{Z}) &
\end{array} \tag{6.45}$$

then we have: For classes $\xi \in H^p(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda), \eta \in H^{d-p-1}(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee})$ we have the equality

$$< \xi, \delta(\eta) >= \delta_d(< r(\xi), \eta >_\partial) \tag{6.46}$$

Non degeneration of the pairing

The spaces $\mathcal{S}^G_{K_f}$ and $\partial\mathcal{S}^G_{K_f}$ are not connected in general. Let us assume that we have a consistent orientation on $\mathcal{S}^G_{K_f}$. Then each connected component M of $\mathcal{S}^G_{K_f}$ is an oriented manifold which is natural embedded into its compactification $\bar{M}$. It is obvious that the cohomology groups are the direct sums of the cohomology groups of the connected components and that we may restrict the pairing to the components

$$H^p(M, \tilde{\mathcal{M}}_\lambda) \times H^{d-p}_c(M, \tilde{\mathcal{M}}_{\lambda^\vee}) \to H^d_c(M, \mathbb{Z}) = \mathbb{Z}. \tag{6.47}$$

We recall the results which are explained in Vol. I 4.8.4. The fundamental group $\pi_1(M)$ is an arithmetic subgroup $\Gamma_M \subset G(\mathbb{Q})$ and $\mathcal{M}_\lambda, \mathcal{M}_{\lambda^\vee}$ are Γ_M modules. For any commutative ring with identity $\mathbb{Z} \to R$ the Γ_M modules $\mathcal{M}_\lambda \otimes R, \mathcal{M}_{\lambda^\vee} \otimes R$ provide local systems $\widetilde{\mathcal{M}_\lambda \otimes} R, \widetilde{\mathcal{M}_{\lambda^\vee} \otimes} R$, and we have the extension of the cup product pairing

$$H^p(M, \widetilde{\mathcal{M}_\lambda \otimes R}) \times H^{d-p}_c(M, \widetilde{\mathcal{M}_{\lambda^\vee} \otimes R}) \to H^d_c(M, R) = R$$

Proposition 6.3.4. *If $R = k$ is a field then the pairing is non degenerate. .*

If R is a Dedekind ring then the pairing then the cohomology may contain some torsion submodules and

$$H^p(M, \widetilde{\mathcal{M}_\lambda \otimes R})/\mathrm{Tors} \times H^{d-p}_c(M, \widetilde{\mathcal{M}_{\lambda^\vee} \otimes R})/\mathrm{Tors} \to H^d_c(M, R) = R$$

is non degenerate.

(See Vol. I 4.8.9)

We want to discuss the consequences of this result for the cohomology of $H^\bullet_?(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$. Before we do this we want to recall some simple facts concerning the representations of the algebraic group $G/\mathbb{Q}$. We consider two highest weights $\lambda, \lambda_1 \in X^*(T \times F)$ which are dual modulo the center. By this we mean that we have (See 6.22)

$$\lambda = \lambda^{(1)} + \delta, \lambda_1 = -w_0(\lambda^{(1)}) + \delta_1 \tag{6.48}$$

Then $\delta + \delta_1$ is a character on $X^*(C' \times F)$ and yields a one dimensional module

$H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \times H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}^\vee_\lambda) \to H^d_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \tilde{\mathcal{M}}^\vee_\lambda) \to H^d_c(\mathcal{S}^G_{K_f}, \mathbb{Z})$ for $G \times F$, of course the action of $G^{(1)}$ on this module is trivial. Then we get a G invariant non trivial pairing

$$\mathcal{M}_{\lambda,F} \times \mathcal{M}_{\lambda_1,F} \to \mathcal{N}_{\lambda\circ\lambda_1}$$

which induces a pairing

$$H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F}) \times H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,F}) \to H^d_c(\mathcal{S}^G_{K_f}, \mathcal{N}_{\lambda\circ\lambda_1}),$$

this only a slight generalization of the previous pairing.

Now we recall that (under certain assumptions) we have the inclusion $\pi_0(\mathcal{S}^G_{K_f}) \hookrightarrow \pi_0(\mathcal{S}^{C'}_{K^{C'}_\infty \times K^{C'}_f})$ and then we get

$$H^d_c(\mathcal{S}^G_{K_f}, \mathcal{N}_{\lambda\circ\lambda_1}) \subset H^0(\mathcal{S}^{C'}_{K^{C'}_\infty \times K^{C'}_f}, \mathcal{N}_{\lambda\circ\lambda_1}) = \bigoplus_{\chi':\text{type}(\chi')=\lambda\circ\lambda_1} F\chi'$$

The character χ' has a restriction to $C(\mathbb{A})$ let us call this restriction χ.

The group $C(\mathbb{A}_f)$ acts on the cohomology groups and this action has an open kernel K^C_f. Hence we can decompose the cohomology groups on the left hand side according to characters

$$H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F}) = \bigoplus_{\zeta_f:\text{type}(\zeta_f)=\delta} H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F})(\zeta_f) \tag{6.49}$$

$$H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,F}) = \bigoplus_{\zeta_{1,f}:\text{type}(\zeta_{1,f})=\delta_1} H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,F})(\zeta_{1,f}). \tag{6.50}$$

With these notations we get another formulation of Poincaré duality.

Proposition 6.3.5. *If we have three algebraic Hecke characters $\zeta_f, \zeta_{1,f}, \chi'_f$ of the correct type and if we have the relation $\zeta_f \cdot \zeta_{1,f} = \chi_f$ then the cup product induces a non degenerate pairing*

$$H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F})(\zeta_f) \times H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,F})(\zeta_{1,f}) \to F\chi'$$

This is an obvious consequence of our considerations above. Fixing the central characters has the advantage that the target space of the pairing becomes one dimensional over F, The field F should contain the values of the characters.

We return to the diagram (6.45) and consider the images $\mathrm{Im}(r^q)(\zeta_f) = \mathrm{Im}(H^q_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F})(\zeta_f) \to H^{d-q-1}_c(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}^\vee_{\lambda,F})(\zeta_f)$ and $\mathrm{Im}(r^{\vee,d-q-1})$. Then the following proposition is an obvious consequence of the non degeneration of the pairing and (6.46)

Proposition 6.3.6. *The images $Im(r^p(\zeta_f))$ and $Im(r^{\vee,d-p-1})(\zeta_{1,f})$ are mutual orthogonal complements of each other with respect to $<\,,\,>_\partial$.*

The pairing in proposition 6.3.5 induces a non degenerate pairing

$$H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F})(\zeta_f) \times H^{d-i}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,F})(\zeta_{1,f}) \to F\chi'.$$

Proof. Let $\eta \in H^{d-p-1}(\zeta_{1,f})$ Then we know from the exactness of the sequence that $\eta \in \mathrm{Im}(r^{\vee,d-p-1})(\zeta_{1,f}) \iff \delta(\eta) = 0 \iff <\delta(\eta), \xi>= 0$ for all $\xi \in H^p(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)(\zeta_f) \iff <\eta, r(\xi)>= 0$ for all $\xi \in H^p(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)(\zeta_f) \iff <\eta, \xi'>_\partial= 0$ for all $\xi' \in \mathrm{Im}(r^q)(\zeta_f)$.

The second assertion is rather obvious. If we have $\xi \in H^p_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)(\zeta_f), \xi_1 \in H^{d-p}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee})(\zeta_f)$ then we can lift either of these classes - say ξ_1- to a class $\tilde{\xi}_1 \in H^p_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)(\zeta_f)$ and then $<\xi_1, \xi_2>=<\tilde{\xi}_1, \xi_2>$. It is clear that the result does not depend on the choice of class which we lift. It is also obvious that the pairing is non degenrate. $\square$

Of course we also have a version of proposition 6.3.6 for the integral cohomology. Since we fixed the level we have only a finite number of possible central characters $\zeta_f, \zeta_{1,f}$ of the required type. The values of these characters evaluated on $C(\mathbb{A}_f)$ lie in a finite extension $F/\mathbb{Q}$ and of of course they are integral. If we now invert a few small primes and pass to a quotient ring $R = \mathcal{O}_F[1/N]$ then we get the decomposition (6.49) but with coefficient systems which are R-modules:

$$H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R}) = \bigoplus_{\zeta_f:\text{type}(\zeta_f)=\delta} H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})(\zeta_f) \tag{6.51}$$

$$H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,R}) = \bigoplus_{\zeta_{1,f}:\text{type}(\zeta_{1,f})=\delta_1} H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,R})(\zeta_{1,f}) \tag{6.52}$$

Then it becomes clear that we get an integral version of proposition 6.3.5 where replace the F-vector space coefficient systems $\tilde{\mathcal{M}}_{\lambda,F}$ by R -module coefficient systems. We get a non degenerate pairing

$$H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})(\zeta_f)/\text{Tors} \times H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,R})(\zeta_{1,f})/\text{Tors} \to R\chi' \tag{6.53}$$

We can also get an integral version of proposition 6.3.6. To formulate it we need a little bit of commutative algebra. Our ring R is a Dedekind ring and all our cohomology groups are finitely generated R modules. If we divide any finitely generated R-module by the subgroups of torsion elements then the result is a projective R-module and it is locally free for Zariski topology.

An element $\xi \in H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})(\zeta_f)/\text{Tors}$ is called *primitive* if the submodule $R\xi$ is locally for the Zariski topology a direct summand or what amounts to the same if $H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})(\zeta_f)/\text{Tors}/R\xi$ is torsion free. The assertion that the above pairing is non degenerate f means:

For any primitive element $\xi \in H^i_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})(\zeta_f)/\text{Tors}$ *we find an element* $\xi_1 \in H^{d-i}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,R})(\zeta_{1,f})/\text{Tors}$ *such the value of the pairing* $< \xi, \xi_1 >= 1$

We can formulate an integral version of proposition 6.3.6 we have the same notations as above but now our coefficient system is $\tilde{\mathcal{M}}_{\lambda,R}$.

Proposition 6.3.7. *Assume that* $H^\bullet(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})$ *and* $H^\bullet(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})$ *are torsion free. Then the images* $Im(r^p(\zeta_f))$ *and* $Im(r^{\vee,d-p-1})(\zeta_{1,f})$ *are mutual orthogonal complements of each other with respect to* $< \, , \, >_\partial$ *.*

The pairing in proposition 6.3.5 induces a non degenerate pairing

$$H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})(\zeta_f)/\text{Tors} \times H^{d-i}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda_1,R})(\zeta_{1,f})/\text{Tors} \to R\chi'.$$

Inner Congruences

We choose a highest weight $\lambda = \lambda^{(1)} + d\delta$ and the dual weight $\lambda^\vee = -w_0(\lambda) - d\delta$. Let us also fix a central character ζ_f whose type is equal to the restriction of $d\delta$ to the central torus C.

We look at the pairing in prop. 6.3.6 where we assume in addition that $\zeta_{1,f} = \zeta_f^{-1}$ and we take the action of the Hecke algebra into account, i.e we look at the decomposition into eigenspaces (see(6.40). Then we get a non degenerate pairing between isotypical subspaces

$$H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F})(\pi_f) \times H^{d-i}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee,F})(\pi_f^\vee) \to F$$

where we assume that the central characters of the summands are ζ_f, ζ_f^{-1}.

If we try to extend this to the integral cohomology. In this case the above decomposition yields decompositions up to isogeny

$$\begin{array}{c} H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})/\mathrm{Tors} \supset \bigoplus_{\pi_f} H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})/\mathrm{Tors}(\pi_f) \\ H^{d-i}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee,R})/\mathrm{Tors} \supset \bigoplus_{\pi_f} H^{d-i}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee,R})/\mathrm{Tors}(\pi_f^\vee) \end{array} \tag{6.54}$$

where we should fix the central characters as above. We choose a pair $\pi_f, \pi_f^\vee$. Then our non degenerate pairing from the above proposition induces a pairing

$$H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,R})/\mathrm{Tors}(\pi_f) \times H^{d-i}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee,R})/\mathrm{Tors}(\pi_f^\vee) \to R \tag{6.55}$$

and this pairing is non degenerate if and only if both modules are direct summands in the above decomposition up to isogeny.

But it may happen that the values of the pairing generate a proper ideal $\Delta(\pi_f) \subset R$, and in this case the above submodules will not be direct summands and this implies that we will have congruences between the Hecke-module π_f and some other module in the decomposition up to isogeny. This yields the *inner congruences.*

The ideal $\Delta(\pi_f)$ should be expressed in terms of L-values, in the classical case this has been done by Hida [Hi].

Chapter 7

The fundamental question

Let Σ be a finite set. Of course any product $V = \otimes H_{\pi_p}$ of finite dimensional absolutely irreducible modules for the $\mathcal{H}_p$, for which $\mathcal{H}_p$ is spherical for all $p \notin \Sigma$ gives us an absolutely irreducible module for the Hecke algebra.

We may ask: Can we formulate non tautological conditions for the irreducible representation V or for the collection $\{\pi_p\}_{p:prime}$, which are necessary or (and) sufficient for the occurrence of $\otimes'_p \pi_p$ in the cohomology

This question can be formulated in the more general framework of the theory automorphic forms, but in this book we only consider "cohomological" (or certain limits of those) automorphic forms. This restricted question is difficult enough. A speculative answer is outlined in the following section

7.0.6 The Langlands philosophy

Let us start from a product $V = \otimes H_{\pi_p}$. For the primes outside the finite set Σ the module H_{π_p} is determined by its Satake parameter ω_p.

The dual group

There is another way of looking at these Satake parameters ω_p. We explain this in the case that $\mathcal{G}/\mathbb{Z}_p$ is a split reductive group. We choose a maximal split torus $\mathcal{T}$ over $\mathbb{Z}$ and a Borel subgroup $\mathcal{B}/\mathbb{Z}$. For any commutative ring with identity ring R we have a canonical isomorphism $X_*(\mathcal{T}) \otimes R^\times \xrightarrow{\sim} \mathcal{T}(R)$, which is given by $\chi \otimes a \mapsto \chi(a)$. Then $\mathcal{T}(\mathbb{Q}_p)/\mathcal{T}(\mathbb{Z}_p) = X_*(\mathcal{T}) \otimes \mathbb{Q}_p^\times/\mathbb{Z}_p^\times = X_*(\mathcal{T})$. We apply this to the maximal split torus $\mathcal{T}/\mathbb{Z}_p \subset \mathbb{G}/\mathbb{Z}_p$. Then $\Lambda(\mathcal{T}) = \operatorname{Hom}(X_*(\mathcal{T}), \mathbb{C}) = X^*(\mathcal{T}) \otimes \mathbb{C}^\times = T^\vee(\mathbb{C})$ where $T^\vee$ is the torus over $\mathbb{Q}$ whose cocharacter module is $X^*(\mathcal{T})$. This torus over $\mathbb{Q}$ is called the dual torus. There is a canonical construction of a dual group ${}^L G/\mathbb{C}$, this is a reductive group with maximal torus $T^\vee$ such that the Weyl group of $T^\vee$ in this dual group is equal to the Weyl group of $\mathcal{T} \subset \mathbb{G}$ (See also (7.0.6)). This dual torus sits in a Borel subgroup ${}^L B \subset^L G$. Recall that we have a canonical pairing

$$<,>: X_*(\mathcal{T}) \times X^*(\mathcal{T}) \to \mathbb{Z},\ \gamma \circ \chi(x) \mapsto x^{<\chi,\gamma>}. \tag{7.1}$$

The positive simple roots in $X^*(T^\vee)$ in the dual group ${}^LG/\mathbb{C}$ are the cocharacters $\alpha_i^\vee \in X_*(\mathcal{T}^{(1)})$ defined by

$$< \alpha_i^\vee, \gamma_j >= \delta_{i,j}.$$

Hence we can interpret $\omega_p \in \Lambda(T) = X^*(\mathcal{T}) \otimes \mathbb{C}^\times = T^\vee(\mathbb{C})$ as a semi simple conjugacy class in ${}^LG(\mathbb{C})$. Remember that ω_p is only determined by the local component π_p up to an element in the Weyl group, hence we only get a conjugacy class.

We assume that $\mathbb{G}/\mathbb{Z}$ is a split reductive group scheme. Then the dual group ${}^LG$ is also split over $\mathbb{Z}$ and the absolutely irreducible highest weight modules $\mathcal{M}_\lambda$ for $\mathbb{G}/\mathbb{Z}$ and the highest weight module attached to χ are defined over $\mathbb{Q}$. Let $\pi_f \in \mathrm{Coh}_!(G, K_f, \lambda)$ be absolutely irreducible and defined over a finite extension $E/\mathbb{Q}$. Hence we see that our absolutely irreducible π_f provides a collection of conjugacy classes $\{\omega(\pi_p) = \omega_p\}_{p\notin\Sigma}$ in the dual group ${}^LG(E)$.

A rather vague but also very bold formulation of the general Langlands philosophy predicts:

The isotypical components under the action of the Hecke algebra, namely the $H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})(\pi_f)$, should correspond to a collection $\{\mathbb{M}(\pi_f, r_\chi)\}_{r_\chi}$ of motives (with coefficients in E). The correspondence should be defined via the equality of certain automorphic and motivic L-functions.

This formulation is definitely somewhat cryptic, we will try to make it a little bit more precise in the following sections.

Such a motive could in principle be a "direct summand" the $H^i(X)$ of a smooth projective scheme $X/\mathbb{Q}$, which in a certain sense is cut out by a projector. In some cases, where the space $\mathcal{S}^G_{K_f}$ "is a Shimura variety", these motives have been constructed, we will discuss this issue in Chap. V.

The cyclotomic case

We consider the special case that $G = \mathbb{G}_m/\mathbb{Q}$ and our coefficient system $\mathbb{Q}(n)$ is given by the character $[n] : x \mapsto x^n$. We fix a level K_f and we consider our isotypical decomposition over $\mathbb{Q}$

$$H^0(\mathcal{S}^G_{K_f}, \mathbb{Q}(n)) = \bigoplus_{\Phi} \mathbb{Q}(\Phi_f).$$

In this case $\mathbb{Q}(\Phi_f)$ is a field, and the action of the group is simply an irreducible action of the group of finite ideles $G(\mathbb{A}_f) = I_{\mathbb{Q},f}$ on the $\mathbb{Q}$-vector space $\mathbb{Q}(\Phi_f)$. If we extend our field to $\bar{\mathbb{Q}}$ we get a decomposition

$$H^0(\mathcal{S}^G_{K_f}, \bar{\mathbb{Q}}(n))) = \bigoplus_{\chi:type(\chi)=[n]} \bar{\mathbb{Q}}(\chi),$$

and the collection of conjugate characters χ are in one to one correspondence with the Φ_f. We can attach two different kinds of L-functions to our isotypical component Φ_f namely an automorphic L-function and a motivic L-function.

Actually we get a collection of such L-functions which are labelled by the embeddings $\iota : \mathbb{Q}(\Phi) \to \bar{\mathbb{Q}} \subset \mathbb{C}$. Such an embedding yields an algebraic Hecke character

$$\chi_f^{(\iota)} = \iota \circ \Phi_f : G(\mathbb{A}_f) = I_{\mathbb{Q},f} \to \bar{\mathbb{Q}}^\times$$

and

$$\chi^{(\iota)} = \iota \circ \Phi : G(\mathbb{Q})\backslash G(\mathbb{A}) = \mathbb{Q}^\times \backslash I_{\mathbb{Q}} \to \mathbb{C}^\times$$

and to any of these Hecke characters we attach the (the automorphic L-function) namely

$$L(\chi^{(\iota)}, s) = \prod_p (1 - \chi^{(\iota)}(p)p^{-s})^{-1}$$

where $\chi^{\ (\iota)}(p) = \chi^{\ (\iota)}(1, 1 \ldots, p, \ldots)$ and it is zero of the character is ramified.

Now we can attach a motive $\mathbb{M}(\Phi)$ to our isotypical component. To do this we assume first that $\mathbb{Q}(\Phi) = \mathbb{Q}$, then we have only one embedding. Then we have $\chi(\underline{x}) = \alpha^n(\underline{x}) = \mid \underline{x} \mid^n$ for some integer n. This is an algebraic Hecke character of type $[-n] : x \mapsto x^{-n}$. Then we attach the motive $\mathbb{Z}(-n)$ to this Hecke character. At this moment we do not need to know what a motive is, the only thing we need to know that it provides a compatible system of ℓ -adic representations of the Galois group: For any prime ℓ we define a module To this motive we attach a motivic L function using the compatible system of ℓ-adic representations. For a prime ℓ and a prime $p \neq \ell$ we have the local Euler factor

$$L_p(\mathbb{Z}(-n), s) = \frac{1}{\det(1 - F_p^{-1} | \mathbb{Z}_\ell(-n)p^{-s})} = \frac{1}{1 - p^n p^{-s}},$$

where F_p is the Frobenius at p. The ℓ-adic representation is unramified outside ℓ and the Frobenius F_p corresponds to p under the reciprocity map r. Hence we see that the Frobenius F_p acts by the multiplication by $\alpha^n(p) = \mid p \mid_p^n = p^{-n}$ on $\mathbb{Z}_\ell(-n)$. In the general case we start from the representation $\Phi_f : I_{\mathbb{Q},f} \to \mathbb{Q}(\Phi_f)^\times$, it is unramified outside a finite set Σ of primes. The reciprocity map from class field theory provides a homomorphism $r : I_{\mathbb{Q},f} \to \ \mathrm{Gal}_\Sigma(\bar{\mathbb{Q}}/\mathbb{Q})_{abelian}$, this is the maximal abelian quotient of the Galois group which is unramified outside Σ, the image of the reciprocity map is dense. If we fix a prime ℓ then we get an ℓ-adic representation

$$\rho(\Phi) : \ \mathrm{Gal}_\Sigma(\bar{\mathbb{Q}}/\mathbb{Q})_{abelian} \to (\mathbb{Q}(\Phi_f) \otimes \mathbb{Q}_\ell)^\times,$$

which is determined by the rule $\rho(\Phi)(F_p) = \Phi_f(p)$. If we now choose an embedding $\iota : \mathbb{Q}(\Phi_f) \to \bar{\mathbb{Q}}$ and an extension $\mathfrak{l}$ of ℓ to a place of $\bar{\mathbb{Q}}$ and we get a one dimensional $\mathfrak{l}$ adic representation

$$\rho(\iota \circ \Phi) : \ \mathrm{Gal}_\Sigma(\bar{\mathbb{Q}}/\mathbb{Q})_{abelian} \to \bar{\mathbb{Q}}_{\mathfrak{l}}^\times,$$

from which we get a motivic L-function $(\mathbb{M}(\Phi) \circ \iota, s)$, whose local factor at p is

$$L_p(\mathbb{M}(\Phi)^{(\iota)}, s) = \frac{1}{1 - \rho(\iota \circ \Phi)(F_p)^{-1}p^{-s}}$$

These are the collections of ℓ-adic rpresentations of our motives $\mathbb{M}(\Phi)$. Then the relation between the automorphic and the ℓ -adic L functions is:

The collection of automorphic L-functions attached to Φ is equal to the collection of motivic L-functions attached to $\mathbb{M}(\Phi^{-1})$.

We will sometimes modify the notation slightly. If χ is an algebraic Hecke character then this datum corresponds to a pair (Φ,ι) and hence we can attach to it a character $\chi_{\mathfrak{l}} : \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \bar{\mathbb{Q}}_{\mathfrak{l}}$ and then we get the equality of local L-factors

$$L_p(\chi,s)=\frac{1}{1-\chi(p)p^{-s}}=\frac{1}{1-\chi_{\mathfrak{l}}^{-1}(F_p)^{-1}p^{-s}}$$

(Nochmal ein wenig besser schreiben!!!!!!!!!!!!!!)

The L-functions

Let us choose a cocharacter $\chi : G_m \to T$, we assume that it is in the positive chamber, i.e. we have $<\chi,\alpha_i>\geq 0$ for all positive simple roots . It yields an element $\chi(p)\in T(\mathbb{Q}_p)$. For $\omega_p\in\Lambda(T)$ we put

$$S_{\chi,\omega_p}=p^{<\chi,\rho>}\sum_{w\in W/W_\chi}\omega_p(w(\chi(p))$$

then we get a formula

$$\int_{\mathrm{ch}(\chi(p))}\phi_{\omega_p}(xg)dg=(S_{\chi,\omega_p}+\sum_{\chi'<\chi}a(\chi,\chi')S_{\chi',\omega_p})\phi_{\omega_p}(x) \tag{7.2}$$

where the χ' are in the positive chamber, $\chi'<\chi$ means that $\chi-\chi'=\sum n_i\chi_i, n_i\geq 0$ and the coefficients $a(\chi,\chi')\in\mathbb{Z}$. The expression on the right hand side is invariant under W and hence only depends on ω_p modulo W. (**Give reference!**)

The number $<\chi,\rho>$ is a half integer, hence $p^{<\chi,\rho>}$ may not lie in a fixed number field if p varies. But for those χ' which may occur in the summation we have $<\chi-\chi',\rho>\in\mathbb{Z}$.

We consider an unramified prime. The theorem of Satake yields that we can define a Hecke operator $S_\chi\in\mathcal{H}_p$ such that $S_\chi*\phi_{\omega_p}=S_{\chi,\omega_p}\phi_{\omega_p}$ and the formula (7.2) tells us that we get another recursion

$$S_\chi=\mathrm{ch}(\chi)+\sum_{\chi'<\chi}b(\chi,\chi')\mathrm{ch}(\chi') \tag{7.3}$$

where again $b(\chi,\chi')\in\mathbb{Z}$.

Since we assume that our absolutely irreducible module $V_{\pi_f},\pi_f=\otimes'\pi_p$ occurs in $\mathrm{Coh}(G,K_f,\lambda)$, the Hecke module is a vector space over a finite extension $F/\mathbb{Q}$. We can conclude that the eigenvalue of the convolution operator $\mathrm{ch}(\chi)$ is in F and it follows that

$$S_{\chi,\omega_p}\in F$$

for any cocharacter χ.

Since we can replace χ by $n\chi$ for any integer $n\geq 1$ it follows that the numbers $w(\chi(p))$ lie in a finite extension of F and the polynomial

$$\prod_{w\in W/W_\chi}(X\cdot\mathrm{Id}-p^{<\chi,\rho>}w(\chi(p)))\in F[X].$$

Our cocharacter $\chi \in X_*(T)$ can also be interpreted as a character in $X^*(T^\vee)$, i.e it is a character on the dual torus. Since we assumed it to be in the positive chamber we can view χ as the highest weight of an irreducible representation $r_\chi :^L G \to \mathrm{Gl}(\mathcal{E}_\chi)$. (Since we assume that G is split the dual group is also split over $\mathbb{Q}$ and hence r_χ is defined over $\mathbb{Q}$.) The eigenvalues of the endomorphism $r_\chi(\omega_p)$ are of the form $\omega_p(w(\chi'(p))$ where $\chi' \leq \chi$ and this implies that the polynomial

$$\det(X \cdot \mathrm{Id} - p^{<\chi,\rho>} r_\chi(\omega_p)|\mathcal{E}_\chi) \in F[X].$$

We attach a local Euler factor to the data $\pi_p, \omega_p = \omega(\pi_p), \chi$:

$$L_p^{\mathrm{rat}}(\pi_f, r_\chi, s) = \frac{1}{\det(\mathrm{Id} - p^{<\chi,\rho>} r_\chi(\omega_p) p^{-s}|\mathcal{E}_\chi)} \tag{7.4}$$

which is a formal power series in the variable p^{-s} with coefficients in F. We define

$$L^{\mathrm{rat}}(\pi_f, r_\chi, s) = \prod_{p\in\Sigma} L_p(\pi_f, r_\chi, s)(\prod_{p\notin\Sigma} \frac{1}{\det(\mathrm{Id} - p^{<\chi,\rho>} r_\chi(\omega_p) p^{-s}|\mathcal{E}_\chi)}), \tag{7.5}$$

at the moment we do not say anything about the Euler factors at the bad primes.

At this moment $L^{\mathrm{rat}}(\pi_f, r_\chi, s)$ is a a product of formal power series in infinitely many variables p^{-s} which in some sense encodes the collection of eigenvalues of the different Hecke eigenvalues.

We want to relate this L -function to some other $L-$ functions which are defined in the theory of automorphic forms.

To define the automorphic L -function we start from an absolutely irreducible Hecke -module V_{π_f} over $\mathbb{C}$, its isomorphism type is still denoted by π_f. This π_f will be the first argument (in our notation) in the automorphic L-function. It has a central character ζ_{π_f} and we assume that this central character is the finite component of a character $\zeta_\pi : C(\mathbb{Q})\backslash C(\mathbb{A}) \to \mathbb{C}^\times$. (In the back of our mind of π_f to be the finite component of an automorphic form π, then this assumption is automatically fulfilled. But for the definition of the L-functions we do not need this.)

Then we define the unitary (automorphic) L-function: Here we require that the central character ζ_{π_f} of π_f is unitary and put

$$L^{\mathrm{unit}}(\pi_f, r_\chi, s) = \prod_{p\in\Sigma} L_p(\pi_f, r_\chi, s)(\prod_{p\notin\Sigma} \frac{1}{\det(\mathrm{Id} - r_\chi(\omega_p) p^{-s}|\mathcal{E}_\chi)}) \tag{7.6}$$

If the central character is not unitary we define the automorphic L-function essentially by the same formula:

$$L^{\mathrm{aut}}(\pi_f, r_\chi, s) = \prod_{p\in\Sigma} L_p(\pi_f, r_\chi, s)(\prod_{p\notin\Sigma} \frac{1}{\det(\mathrm{Id} - r_\chi(\omega_p) p^{-s}|\mathcal{E}_\chi)}) \tag{7.7}$$

This $L-$ function is related to an unitary $L-$ function by a shift in the variable s. The isogeny d_C induces a homomorphism $d' : C(\mathbb{Q})\backslash C(\mathbb{A}) \to C'(\mathbb{Q})\backslash C'(\mathbb{A})$ and it is well known that this map has a compact kernel. We compose ζ_π

with the the norm $|\ | : \mathbb{C}^\times \to \mathbb{R}^\times_{>0}$, this composition is trivial on the kernel of d'. Therefore we find a homomorphism $|\zeta_\pi|^* : C'(\mathbb{A}_f) \to \mathbb{R}^\times_{>0}$ which satisfies $|\ | \circ \zeta_\pi = |\zeta_\pi|^* \circ d'$. We look at the finite components of these characters and put as in (6.3.3)

$$\pi^*_f = \pi_f \otimes (|\zeta_\pi|^*)^{-1}. \tag{7.8}$$

This module has a unitary central character. It is easy to see how the Satake parameter changes under the twisting. We have the homomorphism $T(\mathbb{A}) \to C'(\mathbb{A})$ and therefore $(|\zeta_\pi|^*)^{-1}$ induces also a homomorphism from $T(\mathbb{A}_f)$ to $\mathbb{R}^\times_{>0}$. Then it is clear that we get for the Satake parameters the equality

$$\omega(\pi_p \otimes (|\zeta_\pi|^*_p)^{-1}) = \omega(\pi_p)(|\zeta_\pi|^*_p)^{-1} \tag{7.9}$$

Let us assume that π_f occurs as an isotypical subspace in some $H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C})$, where $\lambda = \lambda^{(1)} + \delta$. The element δ is an element in $X^*(C') \otimes \mathbb{Q}$. To an element $\eta \in X^*(C') \otimes \mathbb{R}$ we have attached an element $|\eta|$ and since ζ_{π_f} is of type $\delta \circ d_C$ we have

$$(|\zeta_\pi|^*)^{-1} = |\delta|.$$

We also have the cocharacter $\chi : \mathbb{G}_m \to T$ then it is clear that the composition $(|\zeta_\pi|^*)^{-1} \circ \chi$ induces a homomorphism $\mathbb{G}_m(\mathbb{Q})\backslash\mathbb{G}_m(\mathbb{A}) \to \mathbb{R}^\times_{>0}$ which is of the form

$$((|\zeta_\pi|^*)^{-1} \circ \chi)_{\mathbb{A}} : \underline{x} \mapsto |\underline{x}|^{<\chi,\delta>}. \tag{7.10}$$

Then we have

$$L^{\mathrm{unit}}(\pi^*_f, r_\chi, s) = L^{\mathrm{aut}}(\pi_f, r_\chi, s+ <\chi, \delta>) \tag{7.11}$$

We now assume that π^*_f is the finite part of a cuspidal unitary representation (See 8.1.5), then the functions $L^{\mathrm{unit}}(\pi^*_f, r_\chi, s)$ are studied in the theory of automorphic forms. The Euler factors are now meromorphic functions in the variable $s \in \mathbb{C}$. Since π^*_f is unitary it follows that the Satake parameters satisfy some bounds and this implies that the infinite product converges if $\Re(s) >> 0$. If for all $p \notin \Sigma$ the representation π^*_p is in the unitary principal series, i.e $|\omega^*_{i,p}| = 1$ then it follows from standard arguments that the infinite product over $p \notin \Sigma$ converges for $\Re(s) > 1$.

It is a conjecture (proved in some cases) that $L^{\mathrm{unit}}(\pi_f, r_\chi, s)$ has analytic continuation into the entire complex plane and that there is a functional equation relating $L^{\mathrm{unit}}(\pi_f, r_\chi, s)$ and $L^{\mathrm{unit}}(\pi^\vee_f, r_\chi, 1-s)$.

But of course any theorem proved for the L-functions $L^{\mathrm{unit}}(\pi^*_f, r_\chi, s)$ translates into a theorem for the automorphic L functions $L^{\mathrm{aut}}(\pi_f, r_\chi, s)$.

Given a automorphic representation π which occurs in the cuspidal spectrum then we may twist it by any character $\xi : C'(\mathbb{Q})\backslash C'(\mathbb{A}) \to \mathbb{R}^\times_{>0}$, this group of characters is equal to $X^*(C') \otimes \mathbb{R}$. We get a principal homogenous space (a torsor) of automorphic representations $\{\pi \otimes \xi\}_{\xi \in \Xi}$.

For the Euler factors $p \notin \Sigma$ we have

$$\frac{1}{\det(\mathrm{Id} - r_\chi((\omega_p)(\pi_p \otimes \xi_p))p^{-s}|\mathcal{E}_\chi)}) = \frac{1}{\det(\mathrm{Id} - r_\chi((\omega_p)(\pi_p\ ))p^{-<\chi,\xi>-s}|\mathcal{E}_\chi)}) \tag{7.12}$$

and hence we get for our automorphic L-function

$$L^{\mathrm{aut}}(\pi_f \otimes \xi_f, r_\chi, s) = L^{\mathrm{aut}}(\pi_f, r_\chi, s+ < \chi, \xi >) \tag{7.13}$$

The representation π^* is then the unique cuspidal (in the above sense) representation in this principal homogeneous spaces $\{\pi \otimes \xi\}_{\xi \in \Xi}$, i.e. it is the unique representation which has a unitary central character. In other words π_f^* provides a trivialization of the torsor. Then we define for any $\pi \otimes \xi$

$$L^{\mathrm{unit}}(\pi_f \otimes \xi_f, r_\chi, s) = L^{\mathrm{unit}}(\pi_f^*, r_\chi, s) \tag{7.14}$$

the unitary L-function is constant on the torsor, i.e. invariant under twisting.

We compare the automorphic $L-$ function to the rational $L-$ function. We start from an absolutely irreducible module π_f which occurs in $\mathrm{Coh}_!(G, K_f, \lambda)$ and which is defined over some finite extension $F/\mathbb{Q}$. As usual we write $\lambda = \lambda^{(1)} + \delta$, (See(6.22)). We know that the central character ζ_{π_f} is an algebraic Hecke character of type δ. Our Hecke module π_f is an absolutely irreducible module over F. If we want to compare its L functions to automorphic L-functions we need to choose an embedding $\iota : F \hookrightarrow \mathbb{C}$ and consider the module $V_{\pi_f} \otimes_{F,\iota} \mathbb{C} = V_{\iota\circ\pi_f}$. The we will see in section 8.1.5 that $\iota \circ \pi_f$ is the finite part of an automorphic representation occurring in the discrete (or the cuspidal) spectrum. Hence we have defined $\tilde{L}^{\mathrm{aut}}(\iota \circ \pi_f, r_\chi, s))$. We can also consider the "extension" of the rational L-function

$$\iota\circ L^{\mathrm{rat}}(\pi_f, r_\chi, s) = \prod_{p\in\Sigma} \iota\circ L_p^{\mathrm{rat}}(\pi_f, r_\chi, s) \prod_{p\notin\Sigma} \frac{1}{\det(\mathrm{Id} - \iota(p^{<\chi,\rho>} r_\chi(\omega_p(\pi_p)))p^{-s}|\mathcal{E}_\chi)}$$

Then it is clear that

$$\iota \circ L^{\mathrm{rat}}(\pi_f, r_\chi, s) = L^{\mathrm{aut}}(\iota \circ \pi_f, r_\chi, s- < \chi, \rho >). \tag{7.15}$$

The central character of $\iota \circ \pi_f$ is of type δ, it follows from (6.22) that some non zero multiple $r\delta \in X^*(T)$. Then we put $< \chi, \delta >= \frac{1}{r} < \chi, r\delta >$, this is a rational number. Then we get

$$\iota \circ L^{\mathrm{rat}}(\pi_f, r_\chi, s) = L^{\mathrm{aut}}(\iota \circ \pi_f, r_\chi, s- < \chi, \delta >) \tag{7.16}$$

We still have another L function which is attached to a Hecke module π_f which occurs in the cohomology, this is the cohomological L function. Let us decompose the representation $\mathcal{E}_\lambda$ into weight spaces

$$\mathcal{E}_\chi = \bigoplus_\nu \mathcal{E}_{\chi,\nu} = \bigoplus_{\nu\in X_{*,+}(T)} \bigoplus_{w\in W/W_\nu} \mathcal{E}_{\chi,w(\nu)}$$

then we get with $m(\nu,\chi) = \dim(\mathcal{E}_{\chi,w(\nu)})$. Such a weight vector space is zero unless we have $\nu < \chi$.

$$\det(\mathrm{Id} - r_\chi(\omega_p)p^{-s}|\mathcal{E}_\chi) = \prod_{\nu\in X_{*,+}(T)} \prod_{w\in W/W_\nu} (1 - \omega_p(w(\nu))p^{-s})^{m(\nu,\chi)}$$

For a given ν we expand the inner product

$$\prod_{w\in W/W_\nu}(1-\omega_p(w(\nu))p^{-s}) = 1-(\sum_{w\in W/W_\nu}\omega_p(w(\nu)))p^{-s}\dots.$$

Now we recall that

$$p^{<\chi,\lambda^{(1)}>-<\chi,\delta>}\mathrm{ch}(\chi) = S_\chi^{(\lambda)}$$

is an operator on the integral cohomology (See (6.27)). Then our recursion formula (7.3) implies that

$$p^{<\chi,\lambda^{(1)}>-<\chi,\delta>}S_{\chi'}$$

is an operator on the integral cohomology, we simply have to observe that $<\chi,\lambda^{(1)}> \geq <\chi',\lambda^{(1)}>$. From this it follows directly that for $\nu\in X_{*,+}(T)$ which occurs as a weight in r_χ we have

$$p^{<\chi,\lambda^{(1)}+\rho>-<\chi,\delta>}\sum_{w\in W/W_\nu}\omega_p(w(\nu))\in\mathcal{O}_F$$

because $<\chi,\lambda^{(1)}> > <\nu,\lambda^{(1)}>$. Then the right hand side in the above formula can be written

$$1-p^{<\chi,\lambda^{(1)}+\rho>-<\chi,\delta>}(\sum_{w\in W/W_\nu}\omega_p(w(\nu)))p^{-s-<\chi,\lambda^{(1)}+\rho>+<\chi,\delta>}\dots$$

We introduce the new variable $s' = s+ <\chi,\lambda^{(1)}+\rho> - <\chi,\delta>$ and put

$$c(\chi,\lambda) = <\chi,\lambda^{(1)}+\rho> - <\chi,\delta> \tag{7.17}$$

$$\prod_{w\in W/W_\nu}(1-p^{c(\chi,\lambda)}\omega_p(w(\nu))p^{-s'}) = 1-p^{c(\chi,\lambda)}(\sum_{w\in W/W_\nu}\omega_p(w(\nu)))p^{-s'}\dots \tag{7.18}$$

Hence we define the cohomological local Euler factor at p

$$L_p^{\mathrm{coh}}(\pi_f,r_\chi,s) = \frac{1}{\det(\mathrm{Id}-p^{c(\chi,\lambda)}r_\chi(\omega_p)p^{-s})}. \tag{7.19}$$

(It seems to be reasonable and very adequate to define for any highest weight λ the modified weight $\tilde{\lambda}=\lambda+\rho$.)

We look at this local Euler factor from a slightly different point of view. Our π_f is an absolutely irreducible module which occurs in the cohomology $H^\bullet_?(\mathcal{S}^G_{K_f},\mathcal{M}_\lambda\otimes F)$, where $F/\mathbb{Q}$ is an abstract (normal) finite extension of $\mathbb{Q}$. For an unramified prime p the local factor is simply a homomorphism $\pi_p:\mathcal{H}_p\to E$. The previous computations show that the denominator is equal to a polynomial in the "variable" p^{-s} and with coefficients in $\mathcal{O}_F$, i.e.

$$\det(\mathrm{Id}-p^{c(\chi,\lambda)}r_\chi(\omega_p)p^{-s}) = 1-A_1(p,\lambda,\chi)(\pi_p)p^{-s}+A_2(p,\lambda,\chi)(\pi_p)p^{-2s}\dots\in\mathcal{O}_F[p^{-s}] \tag{7.20}$$

where the $A_i(p,\lambda,\chi)$ are certain explicitly computable elements in $\mathcal{H}_{\mathbb{Z}}^{(\lambda)}$. (We showed this only for $A_1(p,\lambda,\chi)$ but the same kind of reasoning gives it for the other $A_i(p,\lambda,\chi)$.) In the expression of the right hand side the Satake parameter does not enter.

The cohomological L function is defined as

$$L^{\text{coh}}(\pi_f, r_\chi, s) = \prod_{p\in\Sigma} L_p^{\text{coh}}(\pi_p, r_\chi, s) \prod_{p\notin\Sigma} \frac{1}{1 - A_1(p,\lambda,\chi)(\pi_p)p^{-s} + A_2(p,\lambda,\chi)(\pi_p)p^{-2s}\dots}. \tag{7.21}$$

Again we do not discuss the factors at the primes in Σ.

In the definition of the automorphic L function the Satake parameter is an element in ${}^LG(\mathbb{C})$ or in other words $\omega_p(\nu) \in \mathbb{C}^\times$ and $L_p^{\text{aut}}(\pi_f, r_\chi, s)$ is an honest analytic function in the complex variable s for $\Re(s) >> 0$.

If we want to compare the cohomological L-function to the automorphic L -function we have to pick an element $\iota \in I(F,\mathbb{C})$, then $\iota\circ\pi_f$ is an absolutely irreducible Hecke module over $\mathbb{C}$. To $\iota\circ\pi_p$ belongs a Satake parameter ω_p and then

$$\det(\text{Id} - r_\chi(\omega_p)p^{-s+c(\chi,\lambda)}) = 1 - \iota(A_1(p,\lambda,\chi))(\pi_p))p^{-s} + \iota(A_2(p,\lambda,\chi))(\pi_p)p^{-2s}\dots$$

and this tells us that we have

$$L^{\text{coh}}(\iota\circ\pi_f, r_\chi, s) = L^{\text{aut}}(\iota\circ\pi_f, r_\chi, s - c(\chi,\lambda)) \tag{7.22}$$

Invariance under twisting

We remember that we introduced the quotient $\mathcal{C}' = \mathcal{T}/\mathcal{T}^{(1)}$ and the isogeny $d_C : \mathcal{C} \to \mathcal{C}'$. (See 6.1.1). The map d_C in 1.1 induces a map from our locally symmetric space

$$\mathcal{S}^G_{K_f} \xrightarrow{d_{\mathcal{C}'}} \mathcal{S}^{\mathcal{C}'}_{K_\infty^{\mathcal{C}'}\times K_f^{\mathcal{C}'}}$$

We assume that K_∞ is connected and then $K_\infty^{\mathcal{C}'}$ is also connected.

We can modify our system of coefficients if we replace λ by $\lambda + \delta_1$ with $\delta_1 \in X^*(\mathcal{C}')$. Then δ_1 provides a local coefficient system $\mathbb{Z}[\delta_1]$ on $\mathcal{S}^{\mathcal{C}'}_{K_\infty^{\mathcal{C}'}\times K_f^{\mathcal{C}'}}$ and since $K_\infty^{\mathcal{C}'}$ is connected we get a canonical class

$$e_{\delta_1} \in H^0(\mathcal{S}^{\mathcal{C}'}_{K_\infty^{\mathcal{C}'}\times K_f^{\mathcal{C}'}}, \mathbb{Z}[\delta_1])$$

which generates the rank one submodule of type $|\delta_f|^{-1}$ in the decomposition (6.37). We pull this back by d'_C and we get a class in

$$e_{\delta_1} \in H^0(\mathcal{S}^G_{K_f}, \mathbb{Z}[\delta_1]) \tag{7.23}$$

(see section (6.3.4)). We have the isomorphism $\mathcal{M}_{\lambda,\mathbb{Z}} \otimes \mathbb{Z}[\delta_1] \xrightarrow{\sim} \mathcal{M}_{\lambda+\delta_1,\mathbb{Z}}$ and then the cup product with e_{δ_1} yields an isomorphism

$$H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,\mathbb{Z}}) \cup e_{\delta_1} \xrightarrow{\sim} H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda+\delta_1,\mathbb{Z}}) \tag{7.24}$$

This isomorphism is compatible with the action of the integral Hecke algebra provided we choose the right identification

$$\mathcal{H}^{(\lambda)}_{\mathbb{Z}} \to \mathcal{H}^{(\lambda+\delta_1)}_{\mathbb{Z}}$$

which is given by $a \cdot \mathbf{ch}(\underline{x}_f) \mapsto p^{<\mathbf{ch}(\underline{x}_f),\delta_1>} a \cdot \mathbf{ch}(\underline{x}_f)$.

If we extend the coefficients to F then this cup product yields an isomorphism

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F})(\pi_f) \xrightarrow{\sim} H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda+\delta_1,F})(\pi_f \otimes |\delta_{1,f}|^{-1}) \tag{7.25}$$

Then our cohomological L-function has the property

$$L^{\mathrm{coh}}(\pi_f \otimes |\delta_{1,f}|^{-1}, r_\chi, s) = L^{\mathrm{coh}}(\pi_f, r_\chi, s) \tag{7.26}$$

This invariance under twists is of course also a consequence of the definition in terms of the automorphic L-function.

We may interpret this differently. Our λ is a sum of a semi-simple component $\lambda^{(1)}$ plus an abelian part δ We can use the isomorphisms in (7.25) to define a vector space

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^{(1)}+,F})\{\pi_f\}, \tag{7.27}$$

this vector space has a distinguished isomorphism to any of the $H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda+\delta_1,F})(\pi_f\otimes |\delta_{1,f}|^{-1})$, we could say that it the direct limit of all these spaces. By $\{\sigma_f\}$ we understand the array

$$\{\sigma_f\} = \{\dots, \pi_f \otimes |\delta_{1,f}|^{-1}, \}_{\delta_1 \in X^*(\mathcal{C}')}.$$

Using (7.26) we have now defined $L^{\mathrm{coh}}(\{\pi_f\}, r_\chi, s)$

For any pair $\chi \in X_*(T), \lambda \in X^*(T)$, where χ is in the positive chamber and λ a dominant weight we define the weight

$$\mathbf{w}(\chi,\lambda) =< \chi, \lambda^{(1)} + \rho > . \tag{7.28}$$

Here we observe that χ provides a highest weight representation $r = r_\chi$ of ${}^LG$ and λ a highest weight representation of G so we could also write

$$\mathbf{w}(\chi,\lambda) = \mathbf{w}(r_\chi, \mathcal{M}_\lambda) = \mathbf{w}(r, \mathcal{M}). \tag{7.29}$$

This means that we may consider the weight as a number attached to a pair of irreducible rational representations of ${}^LG$ and G. It also depends only on the semi simple part of λ.

A different look

We could look at the previous discussion from another point of view. Given our coefficient system $\mathcal{M}_\lambda$ where $\lambda = \lambda^{(1)} + \delta$ and an absolutely irreducible module $\pi_f \in \mathrm{Coh}_!(G, \lambda, K_f)$. As explained above we get $X^*(C')$ torsor $(\lambda+\delta', \pi_f \otimes |\delta'_f|)$ of such objects. If we choose a $\iota : F \hookrightarrow \mathbb{C}$ then we can think of $\iota \circ \pi_f$ as the finite part of an automorphic representation π. Then we get a second torsor for the above group $\Xi = X^*(C') \otimes \mathbb{R}$. The inclusion $X^*(C') \hookrightarrow \Xi$ yields an interpolation of the first torsor into the second one. To any element $\pi \otimes \xi$ we defined the automorphic L function $L^{\mathrm{aut}}(\iota \circ \pi_f \otimes \xi_f, r_\chi, s)$. Now the unitary and the cohomological L-function are defined as the automorphic L function of a specific point in the torsor, i.e. a specific trivialization.

To define the unitary L function we choose the specific point for which the central character is unitary, for the cohomological L -function we choose the "optimal" point $\pi_f \otimes |\delta'_f|$ for which we have

$$L_p^{\mathrm{coh}}(\pi_f \otimes |\delta'_f|, r_\chi, s)^{-1} \in \mathcal{O}_F[p^{-s}]. \tag{7.30}$$

If we are investigating analytic questions concerning automorphic forms the unitary L is the right object, but if we want to capture the integral structure of the cohomology we prefer to work with the cohomological L function.

The motives

We consider an isotypical submodule $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda;F})(\pi_f)$ in the inner cohomology. The Langlands philosophy predicts the existence of a collection of pure motives over $\mathbb{Q}$ with coefficients in F.

$$\{\mathbb{M}(\pi_f, r_\chi)\}_{r_\chi}$$

which has certain properties. We will not be absolutely precise in the following but we list certain properties this motive should have. We should assume that π_f is not some kind of exceptional Hecke module (for instance it should not be endoscopic), and I can not give a precise definition what that means. We will make it more precise later when we discuss the case that our group is Gl_n.

This motive should be invariant under twists, i.e. we want that

$$\mathbb{M}(\pi_f \otimes |\delta_f|, r_\chi) = \mathbb{M}(\pi_f, r_\chi)$$

First of all this motive has a Betti-realization $\mathbb{M}(\pi_f, r_\chi)_B$, which is simply an F vector space of dimension $\dim(r_\chi)$. Such a motive has a de-Rham realization $\mathbb{M}(\pi_f, r_\chi)_{dRh}$, this is another F-vector space of the same dimension. It has a descending filtration

$$\mathbb{M}(\pi_f, r_\chi)_{dRh} = F^0(\mathbb{M}(\pi_f, r_\chi)_{de-Rh}) \supset F^1(\mathbb{M}(\pi_f, r_\chi)_{de-Rh}) \supset \dots$$

$$\dots \supset F^{\mathbf{w}}(F^0(\mathbb{M}(\pi_f, r_\chi)_{dRh}) \supset F^{\mathbf{w}+1}(F^0(\mathbb{M}(\pi_f, r_\chi)_{dRh}) = 0.$$

The number $\mathbf{w} = \mathbf{w}(\pi_f, \chi)$ is the weight of the motive it is equal to $\mathbf{w}(\chi, \lambda)$.

Furthermore we have a comparison isomorphism

$$I_{B-dRh} : \mathbb{M}(\pi_f, r_\chi)_B \otimes \mathbb{C} \xrightarrow{\sim} \mathbb{M}(\pi_f, r_\chi)_{dRh} \otimes \mathbb{C},$$

this yields periods and these periods should be related to π_f, this is rather mysterious.

For any prime ℓ and any prime $\mathfrak{l}|\ell$ in F we get a Galois representation

$$\rho(\pi_f,\chi):\ \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to GL(\mathbb{M}(\pi_f, r_\chi)_B \otimes F_{\mathfrak{l}})$$

which is unramified outside $\Sigma \cup \{l\}$ and for any such prime we have

$$\det(\mathrm{Id} - \rho(\pi_f,\chi)(\Phi_p^{-1})p^{-s}, \mathbb{M}(\pi_f, r_\chi)_B \otimes F_{\mathfrak{l}}) = L_p^{\mathrm{coh}}(\pi_f, r_\chi, s)^{-1},$$

or in other words we expect that the semi-simple conjugacy classes

$$\rho(\pi_f,\chi)(\Phi_p^{-1}) \sim p^{c(\chi,\lambda)} r_\chi(\omega_p) \tag{7.31}$$

and hence we want

$$L^{\mathrm{coh}}(\pi_f, r_\chi, s) = L(\mathbb{M}(\pi_f, r_\chi), s)$$

The existence of these hypothetical motives has a lot of consequences. Once we have established such a relation

$$L^{\mathrm{coh}}(\pi_f, r_\chi, s) = L(\mathbb{M}(\pi_f, r_\chi), s)$$

then we can exploit this in both directions. We have a certain chance to prove the conjectural analytic properties and the conjectural functional equation for the L-function of the motive $\mathbb{M}(\pi_f, r_\chi)$, provided we can prove this for $L^{\mathrm{coh}}(\pi_f, r_\chi, s)$. On the automorphic side we know many cases in which we can prove these properties of the L-function using the theory of automorphic forms.

In the other direction we have Deligne's theorem concerning the absolute values of the Frobenius. This implies Ramanujan (more details later)

We seem to be very far away from proving these conjectures, but there are many instances where some parts of this program have been established and there are also some very interesting cases where this correspondence has been verified experimentally.

The case $G = \mathrm{Gl}_n$

Notations for the dual group ^LG

We want to verify formula (7.2) in the special case $G = \mathrm{Gl}_n/\mathbb{Z}$. In this case t we have the cocharacters χ_i which send t to the diagonal matrix $t \mapsto \mathrm{diag}(t,\dots,t,1\dots,1)$ where t is placed to the first i dots. They satisfy $<\chi_i, \alpha_j> = \delta_{i,j}$ for $1 \le i \le n, 1 \le j \le n-1$. They are uniquely determined by this condition modulo the cocharacter χ_n which identifies $\mathbb{G}_m$ with the center. For $1 \le \nu \le n-1$ the cocharacter χ_i determines a maximal parabolic subgroup $P_i \supset T$ whose roots $\Delta_{P_i} = \{\alpha| <\chi_i, \alpha> \ge 0\}$. The parabolic subgroup P_i^- will be the opposite parabolic subgroup.

Let $\eta_i : \mathbb{G}_m \to T$ be the cocharacter which sends t to t on the $i-$ th spot on the diagonal and to 1 at all others. If we identify the module of cocharacters with the character group of the dual torus $T^\vee \subset^L G = \mathrm{Gl}_n$ then the differences $\eta_i - \eta_j$ will be the roots, the simple roots are $\eta_i - \eta_{i+1}$ and the fundamental dominant weights are the semi simple components $(\sum_{i=1}^i \eta_i)^{(1)}$.

Formulas for the Hecke operators

We consider the homomorphism $r : K_p = \mathrm{Gl}_n(\mathbb{Z}_p) \to \mathrm{Gl}_n(\mathbb{F}_p)$ then we check easily that the intersection $K_p \cap \chi_i(p) K_p \chi_i(p)^{-1} = K_p^{(\chi_i(p))}$ is the inverse image of the parabolic subgroup $P_i^-(\mathbb{F}_p)$ under r.

We want to evaluate the integral

$$\int_{K_p \chi_i(p) K_p} \phi_{\omega_p}(x) dx$$

We write choose representatives ξ for the cosets of $K_p/K_p^{(\chi_i(p))}$ and write $K_p = \cup_\xi \xi K_p^{(\chi_i(p))}$. We observe that ϕ_{ω_p} is constant on the cosets $\xi K_p^{(\chi_i(p))}$. Hence we see that

$$\int_{K_p \chi_i(p) K_p} \phi_{\omega_p}(x) dx = \sum_\xi \phi_{\omega_p}(\xi \chi_i(p))) \tag{7.32}$$

The Bruhat decomposition gives us a nice system of representatives for $K_p/K_p^{(\chi_i(p))} = \mathrm{Gl}_n(\mathbb{F}_p)/P_i^-(\mathbb{F}_p)$. Let W_{M_i} be the Weyl group of the standard Levi subgroup $M_i = P_i \cap P_i^-$ and we choose a system of representatives W^{P_i} for W/W_{M_i} Then we get a disjoint decomposition

$$\mathrm{Gl}_n(\mathbb{F}_p) = \bigcup_{w \in W^{P_i}} U_B(\mathbb{F}_p) w P_i^-(\mathbb{F}_p),$$

here U_B is the unipotent radical of the standard Borel subgroup. The function ϕ_{ω_p} is constant on the double cosets. If we write a representative in the form $\xi = uw$ then the factor w is determined by ξ but the factor u is not. This factor is only unique up to multiplication from the right by a factor $u \in U_B^{(w,-)}(\mathbb{F}_p) = U_B(\mathbb{F}_p) \cap w P_i^- w^{-1}(\mathbb{F}_p)$. Hence we may choose our u in the subgroup

$$U_B^{(w,+)}(\mathbb{F}_p) = \prod_{\alpha \in \Delta^+ | <\chi_i, w^{-1}\alpha>>0} U_\alpha(\mathbb{F}_p) \tag{7.33}$$

and our sum in (7.32) becomes

$$\sum_{w \in W^{P_i}} \sum_{u \in U_B^{(w,+)}(\mathbb{F}_p)} \phi_{\omega_p}(uw\chi_i(p))) = \sum_{w \in W^{P_i}} p^{l(w)} \phi_{\omega_p}(w\chi_i(p)w^{-1})) \tag{7.34}$$

where $l(w)$ is the cardinality of the set $\{\alpha \in \Delta^+ | < \chi_i, w^{-1}\alpha >> 0\}$. We recall

the definition of the spherical function and get for our integral

$$\sum_{w \in W/W_{M_i}} p^{l(w)} \omega_p(w\chi_i(p)w^{-1}))|\rho|_p(w\chi_i(p)w^{-1})) = \sum_{w \in W/W_{M_i}} p^{l(w) - <\chi_i, w^{-1}\rho>} \omega_p((w\chi_i)(p)) \tag{7.35}$$

Now one checks easily that $p^{l(w) - <\chi_i, w^{-1}\rho>} = p^{<\chi_i, \rho>}$ and hence we get the desired formula

$$\int_{K_p \chi_i(p) K_p} \phi_{\omega_p}(x) dx = p^{<\chi_i, \rho>} \sum_{w \in W/W_{M_i}} \omega_p((w\chi_i)(p)) \tag{7.36}$$

This is the formula (7.2) for the group Gl_n and the special choice of the cocharacters $\chi = \chi_i$. The only cocharacter $\chi' < \chi_i$ is the trivial cocharacter, in our situation its contribution to (7.2) is zero.

Let us have a brief look at an arbitrary reductive (split or may be only quasisplit) group $G/\mathbb{Q}$, let us assume that the center is a connected torus $C/\mathbb{Q}$. We choose a maximal torus $T/\mathbb{Q}$ which is contained in a Borel subgroup $B/\mathbb{Q}$. We have the homomorphism to the adjoint group $G \to G_{\mathrm{ad}}$ it maps T to $T_{\mathrm{ad}} = T/C$. Again we may also define the fundamental cocharacters $\chi_i : \mathbb{G}_m \to T$ which satisfy $< \chi_i, \alpha_j >= \delta_{i,j}$. They are only well defined modulo cocharacters $\chi : \mathbb{G}_m \to C$ but this does not matter so much. Our above method to compute the eigenvalue of $\mathrm{ch}(\chi_i)$ still works if the cocharacter χ_i is "minuscule" which means that $< \chi_i, \alpha_j > \in \{-1, 0, 1\}$. In this case the formula (7.36) is still valid, again there is no contribution from the trivial character.

We return to $G = \mathrm{Gl}_n$ and to our speculations about motives. We choose a weight module $\mathcal{M}_\lambda$ where $\lambda = \sum_i a_i \gamma_i + d\delta$, where the γ_i are the fundamental weights and δ is the determinant. The a_i are integers and we have the consistency condition $\sum i a_i \equiv nd \mod n$. Let us pick an isotypical submodule $H^\bullet(\mathcal{S}^G_{K_f}, \mathcal{M}_\lambda \otimes F)(\pi_f)$. In section 6.3.2 we define the Hecke operators

$$T^{\mathrm{coh},\lambda}_\chi : H^\bullet_?(\mathcal{S}^G_{K_f}, \mathcal{M}_\lambda) \to H^\bullet_?(\mathcal{S}^G_{K_f}, \mathcal{M}_\lambda)$$

and these endomorphisms induce endomorphisms

$$T^{\mathrm{coh},\lambda}_\chi : H^\bullet_{?,\,\mathrm{int}}(\mathcal{S}^G_{K_f}, \mathcal{M}_\lambda \otimes F)(\pi_f) \to H^\bullet_{?,\,\mathrm{int}}(\mathcal{S}^G_{K_f}, \mathcal{M}_\lambda \otimes F)(\pi_f)$$

Let $\pi_f = \otimes \pi_p$ be an irreducible Hecke module and at an unramified place p let ω_p be the Satake parameter. Our Satake parameter is determined by the n-tuple of numbers

$$\omega_p(\eta_i(p)) = \omega_{i,p} \text{ for } i = 1, \dots, n$$

The cocharacter $\chi_n : \mathbb{G}_m \to T$ identifies $\mathbb{G}_m$ with the center of Gl_n. Our Hecke-module π_f has a central character and this provides a Hecke character

$$\pi_f \circ \chi_n : \mathbb{G}_m(\mathbb{A}_f) = I_{\mathbb{Q},f} \to F^\times$$

The restriction of $\mathcal{M}_\lambda$ to $\mathbb{G}_m$ is the character $\omega_\lambda : t \mapsto t^{nd}$ and the type of $\pi_f \circ \chi_n$ is of course ω_λ.

Our cocharacters χ_i define representations of the dual group which is again Gl_n and in fact χ_1 yields the tautological representation $r_1 : \mathrm{Gl}_n \xrightarrow{\sim} \mathrm{Gl}(V)$. Then χ_i yields the representation $r_i = \Lambda^i(r_1) : \mathrm{Gl}_n \to \mathrm{Gl}(\Lambda^i(V))$. For any subset $I \subset \{1, 2, \dots, n\}$ we define

$$\omega_{I,p} = \prod_{i \in I} \omega_{i,p}$$

and then our formula (7.36) in combination with the formula (6.27) in section 6.3.2 and the observation that $< \chi_i, \delta >= i$ yields

$$T^{\mathrm{coh},\lambda}_{\chi_i}(\pi_p) = p^{<\chi_i, \lambda^{(1)} + \rho> - id} \sum_{I : \# I = i} \omega_{I,p} \tag{7.37}$$

and by the same token we get for the cohomological L-function

$$L^{\mathrm{coh}}(\pi_f, r_\nu, s) = \prod_{p\in S} L_p^{\mathrm{coh}}(\pi_f, r_i, s) \prod_{p\notin S} \Big(\prod_{I:\#I=i} \frac{1}{(1-p^{<\chi_i,\lambda^{(1)}+\rho>-id}\omega_{I,p}p^{-s})} \Big) \tag{7.38}$$

Here we see in a very transparent way the independence of the twist: If we modify λ to $\lambda + r\delta$ then we have to modify π_f to $\pi_f \otimes |\delta_f|^{-r}$. This means that the $\omega_{I,p}$ get multiplied by p^{ir} and the modifications cancel out.

We assume that $\pi_f \in \mathrm{Coh}(H_!^\bullet(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_\lambda))$, then we will see in section 8.1.5 that π_f is essentially unitary. The central character of $\mathcal{M}_\lambda$ is $x \mapsto x^{nd}$ and hence we get that $\pi_f^* = \pi_f \otimes |\delta_f|^d$ is unitary. Then the Satake parameter of π_f^* is given by

$$\omega_{i,p}^* = \omega_{i,p} p^{-d} \text{ for } i = 1, \dots, n \tag{7.39}$$

where the factor $p^{-d} = |p|_p^d$ and we observe that these numbers are also invariant under twists by a power of $|\delta_f|$.

Since the operators $T_{\chi_i}^{\mathrm{coh},\lambda}$ operate on the integral cohomology it follows that the numbers $T_{\chi_i}^{\mathrm{coh},\lambda}(\pi_f)$ are algebraic integers. We easily check that for all $i \leq n$

$$i(<\chi_1, \lambda^{(1)} + \rho > -d) \geq <\chi_i, \lambda^{(1)} + \rho > -id$$

and this implies that the numbers

$$\sum_{I:\#I=i} \prod_{\nu\in I} p^{<\chi_1,\lambda^{(1)}+\rho>-d}\omega_{\nu,p}$$

are algebraic integers and hence we can conclude

The numbers

$$\tilde{\omega}_{i,p} = p^{<\chi_1,\lambda^{(1)}+\rho>-d}\omega_{i,p} = p^{<\chi_1,\lambda^{(1)}+\rho>}\omega_{i,p}^* \tag{7.40}$$

are algebraic integers

Observe that these numbers are invariant under twists by a power of $|\delta_f|$.

We want t make few remarks about the relationship between the automorphic and the cohomological L-functions, especially we comment the shift in the variable s.

For the automorphic L -function we assume that we are over $\mathbb{C}$, we have chosen an embedding $\iota : F \hookrightarrow \mathbb{C}$. If our isotypical Hecke module π_f is cuspidal (see Thm. 8.1.5) then the considerations around this theorem show that π_f is essentially unitary. The center $C = \mathbb{G}_m$, the quotient $C' = \mathbb{G}_m$ and the isogeny $d_C : x \mapsto x^n$.

We come back to the Langlands philosophy. It predicts that for our a "cuspidal" π_f and the cocharacter χ_1 we should be able to attach a motive $\mathbb{M}(\pi_f, r_1) = \mathbb{M}(\pi_f, \chi_1)$ with coefficients in F. This motive provides a compatible system of $\mathfrak{l}$- adic Galois representations

$$\rho_{\mathfrak{l}}(\pi_f, \chi_1) : \ \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \to \mathrm{Gl}_n(F_{\mathfrak{l}}) = \mathrm{Gl}(\mathbb{M}(\pi_f, \chi_1)_{\text{ét},\mathfrak{l}}) \tag{7.41}$$

which are unramified outside $\{l\} \cup S$ and for $p \notin S \cup \{l\}$ we should have

$$\det(\mathrm{Id} - \rho_{\mathfrak{l}}(\pi_f, \chi_1)(\Phi_p^{-1})p^{-s}) = \prod_i (1 - p^{<\chi_1, \lambda^{(1)}+\rho>-d}\omega_{i,p}p^{-s}) \tag{7.42}$$

and this means that up to the local factors at the bad primes we should have

$$L^{\mathrm{mot}}(\mathbb{M}(\pi_f, \chi_1), s) = L^{\mathrm{coh}}(\pi_f, \chi_1, s) \tag{7.43}$$

The existence of the compatible system of Galois representation has been shown by Harris - Kai-Wen Lan -Taylor and Thorne and by P. Scholze.

Once we have the motive for the cocharacter χ_1 we easily get it the other χ_i we simply have to look at the exterior powers $\Lambda^i(\mathbb{M}(\pi_f, \chi_1))$.

Now we see that that numbers $\tilde{\omega}_{\nu,p}$ can be interpreted as the eigenvalues of the Frobenius on $\mathbb{M}_{\text{ét},\mathfrak{l}}(\pi_f, \chi_1)$. Under the assumption that π_f is "cuspidal" we expect that the motive $\mathbb{M}(\pi_f, \chi_1)$ is pure of weight $\mathbf{w}(\chi_1, \lambda)$ we get

$$|\tilde{\omega}_{\nu,p}| = p^{\frac{\mathbf{w}(\chi_1,\lambda)}{2}}$$

and this is the Ramanujan conjecture. We will explain in the section on analytic aspects, that for cuspidal π_f the Ramanujan conjecture says that for any embedding $\iota : F \hookrightarrow \mathbb{C}$ we have

$$|\iota \circ \omega^*_{\nu,p}| = 1$$

This suggests that we call the array $\tilde{\omega}_p = \{\tilde{\omega}_{1,p}, \ldots, \tilde{\omega}_{n,p}\}$ the *motivic* Satake parameter (with respect to the tautological representation r_1 .) Of course it can always be defined, independently of the existence of the motive.

We will see in the next section that the inner cohomology is trivial unless our highest weight is essentially self dual, this means that $\lambda^{(1)} = -w_0(\lambda^{(1)})$. Let us assume that this is the case. If $r_1^\vee$ is the dual of the tautological representation then the eigenvalues of $r_1^\vee(\omega_p)$ are by

$$r_1^\vee(\omega_p) = \{\omega_{1,p}^{-1}, \ldots, \omega_{n,p}^{-1}\}.$$

The highest weight of $r_1^\vee$ is the cocharacter $-\eta_n = \sum_{i=1}^{n-1} \eta_i - \det$ (This has to be read in $X^*(T^\vee)$) Then

$$c(-\eta_n, \lambda) =< \chi_1, -w_0(\lambda^{(1)}) > +d$$

and under our assumption that λ is essentially self dual we know

$$< \chi_1, -w_0(\lambda^{(1)}) >=< \chi_1, \lambda^{(1)} >= \frac{\mathbf{w}(\chi_1, \lambda)}{2}.$$

This implies that the motivic Satake parameters with respect to the dual representation $r_1^\vee$ are the numbers

$$\{p^{<\chi_1,\lambda^{(1)}>+d\delta}\omega_{1,p}^{-1}, \ldots, p^{<\chi_1,\lambda^{(1)}>+d\delta}\omega_{n,p}^{-1}\} \tag{7.44}$$

In the following section on Poincaré duality we will see that for any isotypical module $H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,F})(\pi_f)$ the dual module $\pi_f^\vee$ appears in $H^{d-i}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee,F})$. Then we get an equality of local Euler factors

$$L^{\mathrm{coh}}(\pi_p, r_1^\vee, s) = L^{\mathrm{coh}}(\pi_p^\vee, r_1, s) \tag{7.45}$$

The concept of motives allows us to define the the dual motive. If our motive has weight $\mathbf{w}(M)$ then Poincaré duality suggests that we define the motive

$$\mathbb{M}^\vee = \mathrm{Hom}(\mathbb{M}, \mathbb{Z}(-\mathbf{w}(M)) \tag{7.46}$$

The $\mathfrak{l}$ adic realization as Galoismodule gives us

$$\mathbb{M}^\vee_{\text{ét},\mathfrak{l}} = \mathrm{Hom}(\mathbb{M}_{\text{ét},\mathfrak{l}}, \mathbb{Z}_{\mathfrak{l}}(-\mathbf{w}(M))$$

If $\{\alpha_1, \dots, \alpha_m\}$ are the eigenvalues of Φ_p^{-1} on $\mathbb{M}_{\text{ét},\mathfrak{l}}$ then $\{\alpha_1^{-1} p^{\mathbf{w}(M)}, \dots, \alpha_m^{-1} p^{\mathbf{w}(M)}\}$ are the eigenvalues of Φ_p^{-1} on $\mathbb{M}^\vee_{\text{ét},\mathfrak{l}}$.

Therefore we can say: If we find a motive $\mathbb{M}(\pi_f, \chi_1)$ for π_f the we also find the motive for $\pi_f^\vee$ and we have

$$\mathbb{M}(\pi_f^\vee, \chi_1) = \mathbb{M}(\pi_f, \chi_1)^\vee$$

Chapter 8

Analytic methods

8.1 The representation theoretic de-Rham complex

8.1.1 Rational representations

We start from a reductive group $G/\mathbb{Q}$ for simplicity we assume that the semi simple component $G^{(1)}/\mathbb{Q}$ is quasisplit. There is a unique finite normal extension $F/\mathbb{Q}, F\subset\mathbb{C}$ such that $G^{(1)}\times_{\mathbb{Q}} F$ becomes split, if $T^{(1)}/\mathbb{Q}$ is a maximal torus which is contained in a Borel subgroup $B/\mathbb{Q}$ then the Galois group $\mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ acts on $X^*(T^{(1)}\times_{\mathbb{Q}} F)$ and by permutations on the set of positive roots $\pi_G\subset X^*(T^{(1)}\times_{\mathbb{Q}} F)$ corresponding to $B/\mathbb{Q}$. This action factors over the quotient $\mathrm{Gal}(F/\mathbb{Q})$. Then it also acts on the set of highest weights. Since our group is quasi split we find for any highest weight an absolutely irreducible $G\times_{\mathbb{Q}} F$-module $\mathcal{M}_\lambda$.

$$r: G\times_{\mathbb{Q}} K\to \mathrm{Gl}(\mathcal{M}_\lambda)$$

whose highest weight is λ. Since we assumed that $\mathbb{Q}\subset F\subset\bar{\mathbb{Q}}\subset\mathbb{C}$ we get the extension

$$r_{\mathbb{C}}: (G\times_{\mathbb{Q}} K)\times_K\mathbb{C}\to \mathrm{Gl}(\mathcal{M}_\lambda\otimes_F\mathbb{C}).$$

Given such an absolutely irreducible rational representation, we can construct two new representations. At first we can form the dual $\mathcal{M}^\vee_{\lambda,\mathbb{C}}=\mathrm{Hom}_{\mathbb{C}}(\mathcal{M}_\lambda,\mathbb{C})$ and the complex conjugate $\overline{\mathcal{M}}_{\mathbb{C}}$ of our module $\mathcal{M}_\lambda$. On the dual module we have the contragredient representation $r^\vee$, which is defined by $\phi(r_{\mathbb{C}}(g)(v))=r^\vee_{\mathbb{C}}(g^{-1})(\phi)(v)$.

To get the rational representation on the conjugate module $\bar{\mathcal{M}}\otimes_F\mathbb{C}$, we recall its definition: As abelian groups we have $\mathcal{M}\otimes_F\mathbb{C}=\bar{\mathcal{M}}\otimes_F\mathbb{C}$ but the action of the scalars is conjugated, we write this as $z\cdot_c m=\bar{z}m$. Then the identity gives us an identification

$$\mathrm{End}_{\mathbb{C}}(\mathcal{M}\otimes_F\mathbb{C})=\mathrm{End}_{\mathbb{C}}(\bar{\mathcal{M}}_\lambda\otimes_F\mathbb{C}).$$

Now we define an action $\bar{r}_{\mathbb{C}}$ on $\bar{\mathcal{M}}_\lambda\otimes_F\mathbb{C}$: For $g\in G(\mathbb{C})$ we put

$$\bar{r}_{\mathbb{C}}(g)m=r_{\mathbb{C}}(g)\cdot_c m.$$

This defines an action of the abstract group $G(\mathbb{C})$, but this is in fact obtained from a rational representation. Therefore $\mathcal{M}_{\mathbb{C}}^{\vee}$ and $\overline{\mathcal{M}}_C$ both are given by a highest weight.

The highest weight of $\mathcal{M}_{\lambda}^{\vee}$ is $-w_0(\lambda)$. Herew_0 is the unique element $w_0 \in W$, which sends the system of positive roots Δ^+ into the system $\Delta^- = -\Delta^+$.

The highest weight of $\bar{\mathcal{M}}_{\lambda} \otimes_F \mathbb{C}$ is $c(\lambda)$ where $c \in \mathrm{Gal}(\mathbb{C}/\mathbb{R}) \subset \mathrm{Gal}(F/\mathbb{Q})$ is the complex conjugation acting on $X^*(T \times_{\mathbb{Q}} F)$. So we may say: $\overline{\mathcal{M}_{\lambda C}} = \mathcal{M}_{\bar{\lambda}}$.

We will call the module $\mathcal{M}_{\lambda}$- *conjugate-autodual* or simply *c-autodual* if

$$c(\lambda) = -w_0(\lambda) \tag{8.1}$$

In the following few sections (until 8.1.6 we will always assume that our local system (resp. the corresponding representation) are local systems in $\mathbb{C}$-vector spaces (resp. $\mathbb{C}$-vector spaces $\tilde{\mathcal{M}}_{\lambda}$). Therefore we will suppress the factor $\otimes\mathbb{C}$.

8.1.2 Harish-Chandra modules and $(\mathfrak{g}, K_\infty)$-cohomology.

Now we consider the group of real points $G(\mathbb{R})$, it has the Lie algebra $\mathfrak{g}$, inside this Lie algebra we have the Lie algebra $\mathfrak{k}$ of the group K_∞. We have the notion of a $(\mathfrak{g}, K_\infty)$ module: This is a $\mathbb{C}$-vector space V together with an action of $\mathfrak{g}$ and an action of the group K_∞. We have certain assumptions of consistency:

i) The action of K_∞ is differentiable, this means it induces an action of $\mathfrak{k}$, the derivative of the group action.

ii) The action of $\mathfrak{g}$ restricted to $\mathfrak{k}$ is the derivative of the action of K_∞.

iii) For $k \in K_\infty, X \in \mathfrak{g}$ and $v \in V$ we have

$$(\mathrm{Ad}(k)X)v = k(X(k^{-1}v)).$$

Inside V we have have the subspace of K_∞ finite vectors, a vector v is called K_∞ finite if the $\mathbb{C}$- subspace generated by all translates kv is finite dimensional, i.e. v lies in a finite dimensional K_∞ invariant subspace. The K_∞ finite vectors form a subspace $V^{(K_\infty)}$ and it is obvious that $V^{(K_\infty)}$ is invariant under the action of $\mathfrak{g}$, hence it is a $(\mathfrak{g}, K_\infty)$ sub module of V. We call a $(\mathfrak{g}, K_\infty)$ module a Harish-Chandra module if $V = V^{(K_\infty)}$.

For such a $(\mathfrak{g}, K_\infty)$-module we can write down a complex

$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), V) = \{0 \to V \to \mathrm{Hom}_{K_\infty}(\Lambda^1(\mathfrak{g}/\mathfrak{k}), V) \to \mathrm{Hom}_{K_\infty}(\Lambda^2(\mathfrak{g}/\mathfrak{k}), V) \to \dots\}$$

where the differential is given by

$$d\omega(X_0, X_1, \dots, X_p) = \sum_{i=0}^{p} (-1)^i X_i \omega(X_0, \dots, \hat{X}_i, \dots, X_p) +$$
$$\sum_{0 \le i < j \le p} (-1)^{i+j} \omega([X_i, X_j], X_0, \dots, \hat{X}_i, , \dots, \hat{X}_j, \dots, X_p).$$

A few comments are in order. We have inclusions

$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), V) \subset \mathrm{Hom}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), V) \subset \mathrm{Hom}(\Lambda^\bullet(\mathfrak{g}), V).$$

The above differential defines the structure of a complex for the rightmost term, we have to verify that the leftmost term is a subcomplex, this is not so difficult.

We define the $(\mathfrak{g}, K_\infty)$ cohomology as the cohomology of this complex, i.e.

$$H^\bullet(\mathfrak{g}, K_\infty, V) = H^\bullet(\ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), V)).$$

It is clear that the map

$$H^\bullet(\mathfrak{g}, K_\infty, V^{(K_\infty)}) \to H^\bullet(\mathfrak{g}, K_\infty, V)$$

is an isomorphism.

If we have two $(\mathfrak{g}, K_\infty)$ modules V_1, V_2 and form the algebraic tensor product $W = V_1 \otimes V_2$ the we have a natural structure of a $(\mathfrak{g}, K_\infty)$ -module on W : The group K_∞ acts via the diagonal and $U \in \mathfrak{g}$ acts by the Leibniz-rule $U(v_1 \otimes v_2) = Uv_1 \otimes v_2 + v_1 \otimes Uv_2$. If both modules are Harish-Chandra modules, then the tensor product is also a Harish-Chandra module.

Of course any finite dimensional rational representation of the algebraic group also yields a Harish-Chandra module.

For us the $(\mathfrak{g}, K_\infty)$ module $\mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f)$,- this is the space of functions which are $\mathcal{C}_\infty$ in the variable g_∞- is one of the most important $(\mathfrak{g}, K_\infty)$ -modules. We may also consider the limit over smaller and smaller levels K_f we get the space $\mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A}))$, which consists of those functions on $G(\mathbb{A})$, which are left invariant under $G(\mathbb{Q})$, right invariant under a suitably small open subgroup $K_f \subset G(\mathbb{A}_f)$ and which are $\mathcal{C}_\infty$ in the variable g_∞. On these functions the group $G(\mathbb{A})$ acts by translations from the right, since our functions are $\mathcal{C}_\infty$ we also get an action of the Lie algebra $\mathfrak{g}$. Hence this is also a $(\mathfrak{g}, K_\infty) \times G(\mathbb{A}_f)$-module.

If we fix the level see that $\mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f))$ is a $(\mathfrak{g}, K_\infty) \times \mathcal{H}_{K_f}$, the Hecke algebra acts by convolution. We choose a highest weight module $\mathcal{M}_\lambda$ and apply the previous considerations to the Harish-Chandra module

$$V = \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda.$$

Notice that we can evaluate an element $f \in \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda$ in a point $\underline{g} = (g_\infty, \underline{g}_f)$ and the result $f(\underline{g}) \in \mathcal{M}_\lambda$. The Hecke algebra acts via convolution on the first factor.

Let us assume that our compact subgroup $K_f \subset G(\mathbb{A}_f)$ is neat, i.e. for any $\underline{g} = (g_\infty, \underline{g}_f) \in G(\mathbb{A})$ we have $\underline{g}^{-1}(K_\infty \times K_f)\underline{g} \cap G(\mathbb{Q}) = \{e\}$. In this case we know that $\tilde{\mathcal{M}}$ is a local system and we can form the de-Rham complex $\Omega^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$.

We have an action of the Hecke algebra on this complex and we have the following fundamental fact: $\boxed{\text{Borel}}$

Proposition 8.1.1. *We have a canonical isomorphism of complexes*

$$Hom_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda) \xrightarrow{\sim} \Omega^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda),$$

this isomorphism is compatible with the action of the Hecke algebra on both sides

This is rather clear. We have the projection map

$$q : G(\mathbb{R}) \times G(\mathbb{A}_f) \to G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f = X \times G(\mathbb{A}_f)/K_f$$

let $x_0 \in X \times G(\mathbb{A}_f)/K_f$ be the image of the identity $e \in G(\mathbb{R})$. The differential $D_q(e)$ maps the Lie algebra $\mathfrak{g} =$ tangent space of $G(\mathbb{R})$ at e to the tangent space T_{X,x_0} at $x_0 \times e_f$. This provides the identification $T_{X,x_0} \xrightarrow{\sim} \mathfrak{g}/\mathfrak{k}$.

An element $\omega \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda)$ can be evaluated on a p-tuple $(X_0, X_1, \dots, X_{p-1})$ and the result

$$\omega(X_0, X_1, \dots, X_{p-1}) \in \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda.$$

We want to produce an element $\tilde{\omega}$ in the de-Rham complex $\Omega^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$. Pick a point $x \times \underline{g}_f \in X \times G(\mathbb{A}_f)/K_f$, we find an element $(g_\infty, \underline{g}_f) \in G(\mathbb{R}) \times G(\mathbb{A}_f)$ such that $g_\infty x_0 = x$. Our still to be defined form $\tilde{\omega}$ can be evaluated at a p-tuple $(Y_0, \dots, Y_{p-1})$ of tangent vectors in $x \times \underline{g}_f$ and the result has to be an element in $\mathcal{M}_{\mathbb{C},x}$. We find a p-tuple $(X_0, X_1, \dots, X_{p-1})$ of tangent vectors at x_0 which are mapped to $(Y_0, \dots, Y_{p-1})$ under the differential D_g of the left translation by g. We put $\boxed{\text{Armand}}$

$$\tilde{\omega}(Y_0, \dots, Y_{p-1})(x \times \underline{g}_f) = g_\infty^{-1} \omega(X_0, \dots, X_{p-1})(g_\infty, \underline{g}_f). \tag{8.2}$$

At this point I leave it as an exercise to the reader that this gives the isomorphism we want. We recall that the de-Rham complex (Reference Book Vol. !) computes the cohomology and therefore we can rewrite the de-Rham isomorphism $\boxed{\text{BodeRh}}$

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \xrightarrow{\sim} H^\bullet(\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda) \tag{8.3}$$

From now on the complex $\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda)$ will also be called the de-Rham complex.

By the same token we can compute the cohomology with compact supports $\boxed{\text{BodeRhcs}}$

$$H^\bullet_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \xrightarrow{\sim} H^\bullet(\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_{c,\infty}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda) \tag{8.4}$$

where $\mathcal{C}_{c,\infty}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f)$ are the $\mathcal{C}_\infty$ function with compact support. These isomorphisms are also valid if we drop the assumption that K_f is neat.

The Poincaré duality on the cohomology is induced by the pairing on the de-Rham complexes:

Proposition 8.1.2. *If $\omega_1 \in Hom_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \tilde{\mathcal{M}})$ is a closed form and $\omega_2 \in Hom_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_{\infty,c}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \tilde{\mathcal{M}}^\vee)$ a closed form with compact support in complementary degree then the value of the cup product pairing of the classes $[\omega_1] \in H^p(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda), [\omega_2] \in H^{d-p}_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda{}^\vee)$ is given by*

$$< [\omega_1] \cup [\omega_2] >= \int_{\mathcal{S}^G_{K_f}} < \omega_1 \wedge \omega_2 >$$

(Reference Book Vol. !)

8.1.3 Input from representation theory of real reductive groups.

Let us consider an arbitrary irreducible $(\mathfrak{g}, K_\infty)$- module V. We also assume that for any $\vartheta \in \hat{K_\infty}$ the multiplicity of ϑ in V is finite (we say that V is admissible). Then we can extend the action of the Lie-algebra $\mathfrak{g}$ to an action of the universal enveloping algebra $\mathfrak{U}(\mathfrak{g})$ on V and we can restrict this action to an action of the centre $\mathfrak{Z}(\mathfrak{g})$. The structure of this centre is well known by a theorem of Harish-Chandra, it is a polynomial algebra in $r = \operatorname{rank}(G)$ variables, here the rank is the absolute rank, i.e. the dimension of a maximal torus in $G/\mathbb{Q}$. (See Chap. 4 sect. 4)

Clearly this centre respects the decomposition into K_∞ types, since these K_∞ types come with finite multiplicity we can apply the standard argument, which proves the Lemma of Schur. Hence $\mathfrak{Z}(\mathfrak{g})$ has to act on V by scalars, we get a homomorphism $\chi_V : \mathfrak{Z}(\mathfrak{g}) \to \mathbb{C}$, which is defined by

$$zv = \chi_V(z)v.$$

This homomorphism is called the central character of V.

A fundamental theorem of Harish-Chandra asserts that for a given central character there exist only finitely many isomorphism classes of irreducible, admissible $(\mathfrak{g}, K_\infty)$-modules with this central character.

Of course for any rational finite dimensional representation $r : G/\mathbb{Q} \to \mathrm{Gl}(\mathcal{M}_\lambda)$ we can consider $\mathcal{M}_\lambda \otimes \mathbb{C}$ as $(\mathfrak{g}, K_\infty)$-module. If $\mathcal{M}_\lambda$ is absolutely irreducible with highest weight λ (See chap. IV) then it also has a central character $\chi_{\mathcal{M}} = \chi_\lambda$.

Wigner's lemma: *Let V be an irreducible, admissible $(\mathfrak{g}, K_\infty)$-module, let $\mathcal{M} = \mathcal{M}_\lambda$, a finite dimensional, absolutely irreducible rational representation. Then $H^\bullet(\mathfrak{g}, K_\infty, V \otimes \mathcal{M}_\mathbb{C}) = 0$ unless we have*

$$\chi_V(z) = \chi_{\mathcal{M}^\vee}(z) = \chi_{\mathcal{M}_{\lambda^\vee}}(z) \text{ for all } z \in \mathfrak{Z}(\mathfrak{g})$$

Since we also know that the number of isomorphism classes of irreducible, admissible $(\mathfrak{g}, K_\infty)$-modules with a given central character is finite, we can conclude that for a given absolutely irreducible rational module $\mathcal{M}_\lambda$ the number of isomorphism classes of irreducible, admissible $(\mathfrak{g}, K_\infty)$-modules V with $H^\bullet(\mathfrak{g}, K_\infty, V \otimes \mathcal{M}_\mathbb{C}) \neq 0$ is finite.

The proof of Wigner's lemma is very elegant. We have $\mathcal{M} \otimes V = \mathcal{M}^\vee \otimes V$ and hence we have $H^0(\mathfrak{g}, K_\infty, \mathcal{M} \otimes V) = \operatorname{Hom}(\mathcal{M}^\vee, V)^{(\mathfrak{g}, K_\infty)} = \operatorname{Hom}_{\mathfrak{g}, K_\infty}(\mathcal{M}^\vee, V)$. In [B-W] , Chap.I 2.4 it is shown, that the category of $\mathfrak{g}, K_\infty$ -modules has enough injective and projective elements (See [B-W], I. 2.5) . If I is an injective $\mathfrak{g}, K_\infty$-module then $\mathcal{M} \otimes I$ is also injective because for any $\mathfrak{g}, K_\infty$-module A we have $\operatorname{Hom}(A, \mathcal{M} \otimes I) = \operatorname{Hom}(\mathcal{M}^\vee, I)$. Hence an injective resolution $0 \to V \to I^0 \to I^1 \dots$ yields an injective resolution $0 \to \mathcal{M} \to \mathcal{M} \otimes I^0 \to \mathcal{M} \otimes I^1 \dots$ and from this we get

$$H^q(\mathfrak{g}, K_\infty, \mathcal{M} \otimes V) = \operatorname{Ext}^q_{\mathfrak{g}, K_\infty}(\mathcal{M}^\vee, V).$$

Any $z \in \mathfrak{Z}(\mathfrak{g})$ induces an endomorphism of $\mathcal{M}_\lambda$ and V. Since $\mathrm{Ext}^\bullet$ is functorial in both variables, we see that z induces endomorphisms z_1 (via the action on $\mathcal{M}_\lambda$) and z_2 (via the action on V) on $\mathrm{Ext}^q_{\mathfrak{g},K_\infty}(\mathcal{M}^\vee, V)$. We show that $z_1 = z_2$. This is clear by definition for $\mathrm{Ext}^0_{\mathfrak{g},K_\infty}(\mathcal{M}^\vee, V) = \mathrm{Hom}_{\mathfrak{g},K_\infty}(\mathcal{M}^\vee, V)$: For $z \in \mathfrak{Z}(\mathfrak{g})$ and $\phi \in \mathrm{Hom}_{\mathfrak{g},K_\infty}(\mathcal{M}^\vee, V), m \in \mathcal{M}_\lambda$ we have $z_1\phi(m) = \phi(zm) = z_2(\phi(m))$. To prove it for an arbitrary q we use devissage and induction. We embed V into an injective $\mathfrak{g}, K_\infty$ module I and get an exact sequence

$$0 \to V \to I \to I/V \to 0$$

and from this and $\mathrm{Ext}^q_{\mathfrak{g},K_\infty}(\mathcal{M}_\lambda, I)$ for $q > 0$ we get

$$\mathrm{Ext}^{q-1}(\mathfrak{g}, K_\infty, \mathcal{M}_\lambda, I/V) = \mathrm{Ext}^q(\mathfrak{g}, K_\infty, \mathcal{M}_\lambda, V) \text{ for } q > 0.$$

Now by induction we know $z_1 = z_2$ on the left hand side, so it also holds on the right hand side.

If now $\chi_V \neq \chi_{\mathcal{M}^\vee}$ then we can find a $z \in \mathfrak{Z}(\mathfrak{g})$ such that $\chi_{\mathcal{M}^\vee}(z) = 0, \chi_V(z) = 1$. This implies that $z_1 = 0$ and $z_2 = 1$ on all $\mathrm{Ext}^q(\mathfrak{g}, K_\infty(\mathcal{M}_\lambda, V)$. Since we know that $z_1 = z_2$ we see that the identity on $\mathrm{Ext}^q(\mathfrak{g}, K_\infty(\mathcal{M}_\lambda, V)$ is equal to zero and this implies the assertion.

On the universal enveloping algebra $\mathfrak{U}(\mathfrak{g})$ we have an antiautomorphism $u \mapsto^t u$ which is induced by the antiautomorphism $X \mapsto -X$ on the Lie algebra $\mathfrak{g}$. If V is an admissible $(\mathfrak{g}, K_\infty)$-module, then we can form the dual module $V^\vee$ and if we denote the pairing between $V, V^\vee$ by $< \, , \, >_V$ then

$$< Uv, \phi >_V = < v, ^t U\phi >_V \quad \text{for all } U \in \mathfrak{U}(\mathfrak{g}), v \in V, \phi \in V^\vee.$$

If V is irreducible, then it has a central character and we get

$$\chi_{V^\vee}(z) = \chi_V(^t z).$$

This applies to finite dimensional and infinite dimensional $(\mathfrak{g}, K_\infty)$-modules.

8.1.4 Representation theoretic Hodge-theory.

We consider irreducible unitary representations $G(\mathbb{R}) \to U(H)$. We know from the work of Harish-Chandra:

1) If we fix an isomorphism class ϑ irreducible representations of K_∞ then the isotypical subspace $\dim_{\mathbb{C}} H(\vartheta) \leq \dim(\vartheta)^2$, i.e. ϑ occurs at most with multiplicity $\dim(\vartheta)$.

2) The direct sum $\sum_{\vartheta \subset \hat{K_\infty}} H(\vartheta) = H^{(K)} \subset H$ is dense in H and it is an admissible irreducible Harish-Chandra -module.

We call an irreducible $(\mathfrak{g}, K_\infty)$-module unitary, if it is isomorphic to such an $H^{(K)}$.

For a given $G/\mathbb{R}$ and any rational irreducible module $\mathcal{M}_\lambda$ Vogan and Zuckerman give a finite list of certain irreducible, admissible $(\mathfrak{g}, K_\infty)-$ modules $A_{\mathfrak{q}}(\lambda)$, for which $H^\bullet(\mathfrak{g}, K_\infty, A_{\mathfrak{q}}(\lambda) \otimes \mathcal{M}_\lambda) \neq 0$ they compute these cohomology group. This list contains all unitary, irreducible $(\mathfrak{g}, K_\infty)-$modules, which have non trivial cohomology with coefficients in $\mathcal{M}_\lambda$.

For the following we refer to [B-W] Chap. II ,$\mathbb{S}$ 1-2 . We want to apply the methods of Hodge-theory to compute the cohomology groups $H^\bullet(\mathfrak{g}, K_\infty, V \otimes$

$\mathcal{M}_\lambda$) for an unitary $(\mathfrak{g}, K_\infty)$-module V. This means have a positive definite scalar product $< , >_V$ on V, for which the action of K_∞ is unitary and for $U \in \mathfrak{g}$ and $v_1, v_2 \in V$ we have $< Uv_1, v_2 >_V + < v_1, Uv_2 >_V = 0$.

In the next step we introduce for all p a hermitian form on $\mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda)$. To do this we construct a hermitian form on $\mathcal{M}_\lambda$.

(The following considerations are only true modulo the centre). We consider the Lie algebra and its complexification $\mathfrak{g}_\mathbb{C} = \mathfrak{g} \otimes \mathbb{C}$. On this complex vector space we have the complex conjugation $^- : U \mapsto \bar{U}$. We rediscover $\mathfrak{g}$ as the set of fixed points under $^-$. We also have the Cartan involution Θ which is the involution which has $\mathfrak{k}$ as its fixed point set. Then we get the Cartan decomposition

$$\mathfrak{g} = \mathfrak{k} \oplus \mathfrak{p} \text{ where } \mathfrak{p} \text{ is the -1 eigenspace of } \Theta.$$

The Killing form is negative definite on $\mathfrak{k}$ and positive definite on $\mathfrak{p}$, we have for the Lie bracket $[\mathfrak{p}, \mathfrak{p}] \subset \mathfrak{k}$. We consider the invariants under $^- \circ \Theta$, this is the Lie algebra $\mathfrak{g}_c = \mathfrak{k} \oplus \sqrt{-1} \otimes \mathfrak{p}$. On this real Lie algebra the Killing form is negative definite and $\mathfrak{g}_c$ is the Lie algebra of an algebraic group $G_c/\mathbb{R}$ whose base extension $G_c \otimes_\mathbb{R} \mathbb{C} \xrightarrow{\sim} G \otimes_\mathbb{R} \mathbb{C}$ and whose group $G_c(\mathbb{R})$ of real points is compact (this is the so called compact form of G). We still have the representation $G_c/\mathbb{R} \to \mathrm{Gl}(\mathcal{M}_\lambda)$ which is irreducible and hence we find a hermitian form $< , >_\lambda$ on $\mathcal{M}_\lambda$, which is invariant under $G_c(\mathbb{R})$ and which is unique up to a scalar.

This form satisfies the equations

$$< Um_1, m_2 >_\mathcal{M} + < m_1, Um_2 >_\lambda = 0 \text{ for all } m_1, m_2 \in \mathcal{M}_\lambda, U \in \mathfrak{k}$$

this is the invariance under K_∞ and

$$< Um_1, m_2 >_\mathcal{M} = < m_1, Um_2 >_\lambda \text{ for all } m_1, m_2 \in \mathcal{M}_\lambda, U \in \mathfrak{p}$$

this is the invariance under $\sqrt{-1} \otimes \mathfrak{p}$.

Now we define a hermitian metric on $V \otimes \mathcal{M}_\lambda$, we simply take the tensor product $< , >_V \otimes < , >_\lambda = < , >_{V \otimes \lambda}$. Finally we define the (hermitian) scalar product on $\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda)$. We choose and orthonormal (with respect to the Killing form) basis $E_1, E_2, \ldots, E_d$ on $\mathfrak{p}$, we identify $\mathfrak{g}/\mathfrak{k} \xrightarrow{\sim} \mathfrak{p}$. Then a form $\omega \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda)$ is given by its values $\omega(E_I) \in V \otimes \mathcal{M}_\lambda$, where $I = \{i_1, i_2, \ldots, i_p\}$ runs through the ordered subsets of $\{1, 2, \ldots, d\}$ with p elements. For $\omega_1, \omega_2 \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda)$ we put

$$< \omega_1, \omega_2 > = \sum_{I, |I|=p} < \omega_1(E_I), \omega_2(E_I) >_{V \otimes \lambda} \tag{8.5}$$

Now we can define an adjoint operator

$$\delta : \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda) \to \mathrm{Hom}_{K_\infty}(\Lambda^{p-1}(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda), \tag{8.6}$$

which can be defined by a straightforward calculation. We simply write a formula for δ: For an element E_i we define $E_i^*(v \otimes m) = -E_i v \otimes m + v \otimes E_i m$. Then we can define δ by the following formula:

We have to evaluate $\delta(\omega)$ on $E_J = (E_{i_1}, \dots, E_{i_{p-1}})$ where $J = \{i_1, \dots, i_{p-1}\}$. We put

$$\delta(\omega)(E_J) = \sum_{i \notin J} (-1)^{p(i, J\cup\{i\})} E_i^* \omega_{J\cup\{i\}},$$

where $p(i, J\cup\{i\})$ denotes the position of i in the ordered set $J\cup\{i\}$. With this definition we get for a pair of forms $\omega_1 \in \mathrm{Hom}_{K_\infty}(\Lambda^{p-1}(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda)$ and $\omega_2 \in \mathrm{Hom}_{K_\infty}(\Lambda^{p}(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda)$ (See [B-W], II, prop. 2.3)

$$< d\omega_1, \omega_2 >=< \omega_1, \delta\omega_2 > \tag{8.7}$$

We define the Laplacian $\Delta = \delta d + d\delta$. Then we have ([B-W] , II ,Thm.2.5)

$$< \Delta\omega, \omega >\geq 0 \text{ and we have equality if and only if } d\omega = 0, \delta\omega = 0 \tag{8.8}$$

Inside $\mathfrak{Z}(\mathfrak{g})$ we have the the Casimir operator C (See Chap. 4). An element $z \in \mathfrak{Z}(\mathfrak{g})$ acts on $V \otimes \mathcal{M}_\lambda$ by $z \otimes \mathrm{Id}$ via the action on the first factor and by the scalar $\chi_\lambda(z)$ via the action on the second factor. Then we have

Kuga's lemma : *The action of the Casimir operator and the Laplace operator on $Hom_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda)$ are related by the identity*

$$\Delta = C \otimes Id - \chi_\lambda(C).$$

If the $\mathfrak{g}, K_\infty$ module is irreducible, then Δ acts by multiplication by the scalar $\chi_V(C) - \chi_\lambda(C)$

This has the following consequence

If V is an irreducible unitary $\mathfrak{g}, K_\infty$- module and if $\mathcal{M}_\lambda$ is an irreducible representation with highest weight λ then

$$H^\bullet(\mathfrak{g}, K_\infty, V \otimes \mathcal{M}_\mathbb{C}) = \begin{cases} 0 & \text{if } \chi_V(C) - \chi_\lambda(C) \neq 0 \\ Hom_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), V \otimes \mathcal{M}_\lambda) & \text{if } \chi_V(C) - \chi_\lambda(C) = 0 \end{cases}.$$

This only applies for unitary $\mathfrak{g}, K_\infty$-modules, but for these it is much stronger: It says that under the assumption $\chi_V(C) = \chi_\lambda(C)$ we have $\chi_V = \chi_\lambda$ (we only have to test the Casimir operator) and it says that all the differentials in the complex are zero.

8.1.5 Input from the theory of automorphic forms

We apply this to the spaces of square integrable functions on $G(\mathbb{Q})\backslash G(\mathbb{A})/K_f$. Because of the presence of a non trivial center, we have to consider functions which transform in a certain way under the action of the center. We may assume that coefficient system $\mathcal{M}_\lambda$ has a central character and this central character defines a character ζ_λ on the maximal $\mathbb{Q}$-split torus $S \subset C$. This character can be evaluated on the connected component of the identity of the real valued points and induces a (continuous) homomorphism $\zeta_\infty : S^0(\mathbb{R}) \to \mathbb{R}^\times_{>0}$. Then we define

$$\mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1}) \tag{8.9}$$

to be the subspace of those $\mathcal{C}_\infty$ functions which satisfy $f(z_\infty \underline{g}) = \zeta_\infty^{-1}(z_\infty)f(\underline{g})$ for all $z_\infty \in S^0(\mathbb{R}), \underline{\in} G(\mathbb{A})$. The isogeny $d_C : C \to C'$ (see 6.1.1) induces an isomorphism $S^0(\mathbb{R}) \xrightarrow{\sim} S'^{,0}(\mathbb{R})$, where S' is the maximal $\mathbb{Q}$ split torus in C'. Therefore we get a character $\zeta'_\infty : S'^{,0}(\mathbb{R}) \to \mathbb{R}^\times_{>0}$ and this is also a character $\zeta'_\infty : G(\mathbb{R}) \to \mathbb{R}^\times_{>0}$ and its restriction to $S^0(\mathbb{R})$ is ζ_∞. If now $f \in \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})$ then

$$f(\underline{g})\zeta'_\infty(\underline{g}) \in \mathcal{C}_\infty(G(\mathbb{Q})S^0(\mathbb{R})\backslash G(\mathbb{A})/K_f) \tag{8.10}$$

We say that $f \in \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})$ is square integrable if

$$\int_{(G(\mathbb{Q})S^0(\mathbb{R})\backslash G(\mathbb{A})/K_f)} |f(\underline{g})\zeta'_\infty(\underline{g})|^2 d\underline{g} < \infty \tag{8.11}$$

and this allows us to define the Hilbert space $L^2(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})$. Since the space $(G(\mathbb{Q})S^0(\mathbb{R})\backslash G(\mathbb{A})/K_f)$ has finite volume we know that

$$\zeta'_\infty \in L^2(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1}).$$

The group $G(\mathbb{R})$ acts on $\mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})$ by right translations and hence we get by differentiating an action of the universal enveloping algebra $\mathfrak{U}(\mathfrak{g})$ on it. We define by $\mathcal{C}_\infty^{(2)}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})$ the subspace of functions f for which Uf is square integrable for all $U \in \mathfrak{U}(\mathfrak{g})$.

This allows us to define a sub complex of the de-Rham complex $\boxed{\text{Ltwo}}$

$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty^{(2)}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1}) \otimes \mathcal{M}_\lambda). \tag{8.12}$$

We will not work with this complex because its cohomology may show some bad behavior. (See remark below).

We do something less sophisticated, we simply define $H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \subset H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ to be the image of the cohomology of the complex (8.12) in the cohomology. Hence $H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ is the space of cohomology classes which can be represented by square integrable forms.

Remark: Some authors also define L^2 de-Rham complexes, using the above complex (8.12) and then they take suitable completions to get complexes of Hilbert spaces. These complexes also give cohomology groups which run under the name of L^2-cohomology. These L^2-cohomology groups are related but not necessarily equal to our $H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$. They can be infinite dimensional.

The Hilbert space $L^2(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})$ is a module for $G(\mathbb{R}) \times \mathcal{H}_{K_f}$ the group $G(\mathbb{R})$ acts by unitary transformations and the algebra $\mathcal{H}_{K_f}$ is selfadjoint.

Let us assume that $H = H_{\pi_\infty \times \pi_f}$ is an irreducible unitary module for $G(\mathbb{R}) \times \mathcal{H} = \bigotimes'_p \mathcal{H}_p$ and assume that we have an inclusion of this $G(\mathbb{R}) \times \mathcal{H}$-module

$$j : H \hookrightarrow L^2(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1}).$$

It follows from the finiteness results in 8.1.4 that induces an inclusion into the space of square integrable $\mathcal{C}_\infty$ functions

$$H^{(K_\infty)} \hookrightarrow \mathcal{C}_\infty^{(2)}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})^{(K_\infty)}.$$

We consider the $(\mathfrak{g}, K_\infty)-$ cohomology of this module with coefficients in our irreducible module $\mathcal{M}_\lambda$, we assume $\chi_V(C) = \chi_\lambda(C)$. We have $H^\bullet(\mathfrak{g}, K_\infty, H \otimes \mathcal{M}_\lambda) = \mathrm{Hom}_{K_\infty}(\mathfrak{g}, K_\infty, H^{(K_\infty)} \otimes \mathcal{M}_\lambda)$ and get

$$H^\bullet(\mathfrak{g}, K_\infty, H^{(K_\infty)} \otimes \mathcal{M}_\mathbb{C}) \xrightarrow{j^\bullet} H^\bullet(\mathfrak{g}, K_\infty, \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})^{(K_\infty)} \otimes \mathcal{M}_\lambda).$$

This suggests that we try to "decompose" $\mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \zeta_\infty^{-1})^{(K_\infty)}$ into irreducibles and then investigate the contributions of the irreducible summands to the cohomology. Essentially we follow the strategy of [Bo-Ga] and [Bo-Ca] but instead of working with complexes of Hilbert spaces we work with complexes of $\mathcal{C}_\infty$ forms and modify the arguments accordingly.

It has been shown by Langlands, that we have a decomposition into a discrete and a continous spectrum

$$L^2(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) = L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f) \oplus L^2_{\mathrm{cont}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f),$$

where $L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$ is the closure of the sum of all irreducible closed subspaces occuring in $L^2(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f)$ and where $L^2_{\mathrm{cont}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$ is the complement.

The discrete spectrum $L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$ contains as a subspace the *cuspidal spectrum* $L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$:

A function $f \in L^2(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$ is called a *cusp form* if for all proper parabolic subgroups $P/\mathbb{Q} \subset G/\mathbb{Q}$, with unipotent radical $U_P/\mathbb{Q}$ the integral

$$\mathcal{F}^P(f)(g) = \int_{U_P(\mathbb{Q})\backslash U_P(\mathbb{A})} f(\underline{u}\underline{g})d\underline{u} = 0,$$

this means that the integral is defined for almost all $\underline{g}$ and zero for almost all $\underline{g}$. The function $\mathcal{F}^P(f)(\underline{g})$, which is an almost everywhere defined function on $P(\mathbb{Q})\backslash G(\mathbb{A})/K_f$ is called the constant Fourier coefficient of f along $P/\mathbb{Q}$. The cuspidal spectrum the the intersection of all the kernels of the $\mathcal{F}^P$.

If our group is anisotropic, then it does not have any proper parabolic subgroup and in this case we have $L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f) = L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f) = L^2(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$.

For any unitary $G(\mathbb{R}) \times \mathcal{H}$- module $H_\pi = H_{\pi_\infty} \otimes H_{\pi_f}$ we put $W_{\pi,\mathrm{cusp}} = \mathrm{Hom}_{G(\mathbb{R})\times\mathcal{H}}(H_\pi, L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f))$. We can ignore the $\mathcal{H}$-module structure and define

$$W_{\pi_\infty,\mathrm{cusp}} = \mathrm{Hom}_{G(\mathbb{R})}(H_{\pi_\infty}) \otimes H_{\pi_f}, L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)).$$

It has been shown by Gelfand-Graev and Langlands that

$$m_{\mathrm{cusp}}(\pi_\infty) = \sum_{\pi_f} \dim(W_{\pi,\mathrm{cusp}}) < \infty.$$

We get a decomposition into isotypical subspaces

$$L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f) = \overline{\bigoplus_{\pi_\infty\otimes\pi_f} (L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)(\pi_\infty \times \pi_f)},$$

where $(L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)(\pi_\infty \times \pi_f)$ is the image of $W_{\pi,\mathrm{cusp}} \otimes H_\pi$ in $L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$.

The cuspidal spectrum has a complement in the discrete spectrum, this is the *residual spectrum* $L^2_{\mathrm{res}}((G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$. It is called residual spectrum, because the irreducible subspaces contained in it are obtained by residues of Eisenstein classes.

Again we define $W_{\pi,\mathrm{res}} = \mathrm{Hom}_{G(\mathbb{R})\times\mathcal{H}}(H_\pi, L^2_{\mathrm{res}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f))$, (resp. $W_{\pi_\infty,\mathrm{res}} = \mathrm{Hom}_{G(\mathbb{R})}(H_{\pi_\infty}, L^2_{\mathrm{cusp}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f))$, and it is a deep theorem of Langlands that $m_{\mathrm{res}}(\pi_\infty) = \dim(W_{\pi_\infty,\mathrm{res}}) < \infty$. Hence we get a decomposition

$$L^2_{\mathrm{res}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f) = \overline{\bigoplus_{\pi_\infty\otimes\pi_f} (L^2_{\mathrm{res}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)(\pi_\infty \times \pi_f)}.$$

If our group $G/\mathbb{Q}$ is isotropic, then the one dimensional space of constants is in the residual (discrete) spectrum but not in the cuspidal spectrum.

Langlands has given a description of the continuos spectrum using the theory of Eisenstein series, we have a decomposition $\boxed{\text{decomp-cont}}$

$$L^2_{\mathrm{cont}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f) = \overline{\bigoplus_{\Sigma} \tilde{H}^+_P(\pi_\Sigma)}, \tag{8.13}$$

we briefly explain this decomposition following [Bo-Ga]. The Σ are so called cuspidal data, this are pairs (P, π_Σ) where P is a proper parabolic subgroup and π_Σ is a representation of $M(\mathbb{A}) = P(\mathbb{A})/U(\mathbb{A})$ occurring in the discrete spectrum $L^2_{\mathrm{cusp}}(M(\mathbb{Q})\backslash M(\mathbb{A}))$.

Let $M^{(1)}/\mathbb{Q}$ be the semi simple part of M and recall that C/Q was the center of $G/\mathbb{Q}$. We consider the character module $Y^*(P) = \mathrm{Hom}(C\cdot M^{(1)}, \mathbb{G}_m)$. The elements $Y^*(P)\otimes\mathbb{C}$ provide homomorphisms $\gamma\otimes z : M(\mathbb{A})/C(\mathbb{A})M^{(1)}(\mathbb{A}) \to \mathbb{C}^\times$. (See (6.14)). The module $Y^*(P)\otimes\mathbb{Q}$ comes with a canonical basis which is given by the dominant fundamental weights γ_μ which are trivial on $M^{(1)}$. We define

$$\Lambda_\Sigma = Y^*(P) \otimes i\mathbb{R} = \{\sum_\mu \gamma_\mu \otimes it_\mu | t_\mu \in \mathbb{R}\}$$

this is a group of unitary characters. For $\sigma \in \Lambda_\Sigma$ we define the unitarily induced representation

$$\begin{gathered}\mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} \pi_\Sigma \otimes (\sigma + \rho_P) = I_P^G \pi_\Sigma \otimes \sigma \\ \{f : G(\mathbb{A}) \to L^2_{\mathrm{res}}(M(\mathbb{Q})\backslash M(\mathbb{A}))(\pi_\Sigma) | f(\underline{pg}) = (\sigma + |\rho_P|)(\underline{p})\pi_\Sigma(\underline{p}) f(\underline{g})\}\end{gathered} \tag{8.14}$$

where of course $\underline{p} \in P(\mathbb{A}), \underline{g} \in G(\mathbb{A})$ and $\rho_P \in Y^*(P) \otimes \mathbb{Q}$ is the half sum of the roots in the unipotent radical of P. This gives us a unitary representation of $G(\mathbb{A})$. Let d_Σ be the Lebesgue measure on Λ_Σ then we can form the direct integral unitary representations

$$H_P(\pi_\Sigma) = \int_{\Lambda_\Sigma} I_P^G \pi_\Sigma \otimes \sigma \; d_\Sigma \sigma \tag{8.15}$$

The theory of Eisenstein series gives us a homomorphism of $G(\mathbb{R})\times\mathcal{H}$ -modules

$$\mathrm{Eis}_P(\pi_\Sigma) : H_P(\pi_\Sigma) \to L^2_{\mathrm{cont}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f). \tag{8.16}$$

Let us put

$$\Lambda^+_\Sigma = \{\sum_\mu \gamma_\mu \otimes it_\mu | t_\mu \geq 0\}$$

then the restriction

$$\mathrm{Eis}_P(\pi_\Sigma) : H^+_P(\pi_\Sigma) = \int_{\Lambda^+_\Sigma} I^G_P \pi_\Sigma \otimes \sigma \; d_\Sigma\sigma \to L^2_{\mathrm{cont}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f). \tag{8.17}$$

is an isometric embedding. The image will be denoted by $\tilde{H}^+_P(\pi_\Sigma)$ these spaces are the elementary subspaces in [B-G]. Two such elementary subspaces $\tilde{H}^+_P(\pi_\Sigma), \tilde{H}^+_{P_1}(\pi_{\Sigma_1})$ are either orthogonal to each other or they are equal. We get the above decomposition if we sum over a suitable set of representatives of cuspidal data.

Now we are ready to discuss the contribution of the continuous spectrum to the cohomology. If we have a closed square integrable form

$$\omega \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), \mathcal{C}^2_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda),$$

then we can decompose it

$$\omega = \omega_{\mathrm{res}} + \omega_{\mathrm{cont}},$$

both summands are $\mathcal{C}^2_\infty$ and closed.

Proposition 8.1.3. *The cohomology class* $[\omega_{\mathrm{cont}}]$ *is trivial.*

Proof. This now the standard argument in Hodge theory, but this time we apply it to a continuous spectrum instead of a discrete one. We follow Borel-Casselman and prove their Lemma 5.5 (See[B-C]) in our context. We may assume that ω_∞ lies in one of the summands, i.e. $\omega_{\mathrm{cont}} = \mathrm{Eis}(\int_{\Lambda_\Sigma} \omega^\vee(\sigma) d_\Sigma\sigma)$ where $\omega^\vee(\sigma) \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), I^G_P\pi_\Sigma \otimes \sigma \otimes \mathcal{M}_\lambda))$ is the Fourier transform of ω_∞ in the L^2., (theorem of Plancherel). As it stands the expression $\int_{\Lambda_\Sigma} \omega^\vee(\sigma) d_\Sigma\sigma)$ does not make sense because the integrand is in L^2 and not necessarily in L^1. If we choose a symmetric positive definite quadratic form $h(\sigma) = \sum_{\nu,\mu} b_{\nu,\mu} t_\nu t_\mu$ and a positive real number τ then the function

$$h_\tau(\sigma) = (1 + \tau h(\sigma)^m)^{-1} \in L^2(\Lambda_\Sigma)$$

and then $\omega^\vee(\sigma)h_\tau(\sigma)$ is in L^1 and by definition

$$\lim_{\tau\to 0} \int_{\Lambda_\Sigma} \omega^\vee(\sigma)h_\tau(\sigma)d_\Sigma\sigma) = \int_{\Lambda_\Sigma} \omega^\vee(\sigma)d_\Sigma\sigma \tag{8.18}$$

where the convergence is in the L^2 sense. Since $\omega_\infty \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), I^G_P\pi_\Sigma \otimes \sigma \otimes \mathcal{M}_\lambda)$ we get get that $\omega^\vee(\sigma)$ has the following property

For any polynomial $P(\sigma) = \sum a_{\underline{\mu}} t^{\underline{\mu}}$ in the variables t_μ and with real coefficients the section $\boxed{\text{diffmult}}$

$$\omega^\vee(\sigma)P(\sigma) \text{ is square integrable} \tag{8.19}$$

this follows from the well known rules that differentiating a function provides multiplication by the variables for the Fourier transform.

The Lemma of Kuga implies

$$\Delta(\omega^\vee(\sigma)) = (\chi_\sigma(C) - \chi_\lambda(C))\omega^\vee(\sigma)$$

and if $\sigma = \sum \gamma_\mu \otimes it_\mu\mu$ the eigenvalue is

$$\chi_\sigma(C) - \chi_\lambda(C) = \sum a_{\nu,\mu} t_\nu t_\mu + \sum b_\mu t_\mu + c_{\pi_\Sigma} - c_\lambda. \tag{8.20}$$

where c_{π_Σ} is the eigenvalue of the Casimir operator of $M^{(1)}$ on π_Σ If the $t_\mu \in \mathbb{R}$ then this expression is always ≤ 0 especially we see that the quadratic form on the right hand side is negative definite. This implies that for $\sigma \in \Lambda_F$ the expression $\chi_\sigma(C) - \chi_\lambda(C)$ assumes a finite number of maximal values all of them ≤ 0 and hence

$$V_\Sigma = \{\sigma | \chi_\sigma(C) - \chi_\lambda(C) = 0\} \tag{8.21}$$

is a finite set of point. This set has measure zero, since we assumed that P was a proper parabolic subgroup. The of σ for which $H^\bullet(\mathfrak{g}, K_\infty, H_{\Lambda_\Sigma}(\sigma) \otimes \mathcal{M}_\mathbb{C}) \neq 0$ is finite. We choose a $\mathcal{C}_\infty$ function $h_\Sigma(\sigma)$ which is positive, which takes value 1 in a small neighborhood of V_Σ, which takes values ≤ 1 in a slightly larger neighborhood and which is zero outside this second neighborhood. Then we write

$$\omega_\infty = \text{ Eis}(\int_{\Lambda_\Sigma^+} h_\Sigma(\sigma)\omega^\vee(\sigma) d_\Sigma \sigma) + \text{ Eis}(\int_{\Lambda_\Sigma^+} (1 - h_\Sigma(\sigma))\omega^\vee(\sigma) d_\Sigma \sigma)$$

We have $d\omega^\vee(\sigma) = 0$ and hence we get

$$\Delta((1 - h_\Sigma(\sigma))\omega^\vee(\sigma) = d\big((\chi_\sigma(C) - \chi_\lambda(C))(1 - h_{\Sigma(\sigma)})\delta\omega^\vee(\sigma)\big)$$

and this implies that

$$\text{Eis}(\int_{\Lambda_\Sigma^+} (1 - h_\Sigma(\sigma))\omega^\vee(\sigma) d_\Sigma \sigma) = d \text{ Eis}(\int_{\Lambda_\Sigma^+} (1 - h_\Sigma(\sigma))(\chi_\sigma(C) - \chi_\lambda(C))^{-1}\delta\omega^\vee(\sigma) d_\Sigma \sigma)$$

It is clear that the integrand in the second term- $\int_{\Lambda_\Sigma^+}(1 - h_\Sigma(\sigma))(\chi_\sigma(C) - \chi_\lambda(C))^{-1}\delta\omega^\vee(\sigma)$ still satisfies (8.19) and then our well known rules above imply that $\psi = \text{ Eis}(\int_{\Lambda_\Sigma^+}(1 - h_\Sigma(\sigma))(\chi_\sigma(C) - \chi_\lambda(C))^{-1}\delta\omega^\vee(\sigma) d_\Sigma \sigma)$ is $\mathcal{C}^2_\infty$. Therefore the second term in our above formula is a boundary.

$$\omega_{\text{cont}} = \int_{\Lambda_\Sigma} h_\Sigma(\sigma)\omega(\sigma) d_\Sigma \sigma + d\psi.$$

This is true for any choice of h_Σ. Hence the scalar product $< \omega - d\psi, \omega - d\psi >$ can be made arbitrarily small. Then we claim that the cohomology class $[\omega] \in H^\bullet(\text{ Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda)$ must be zero. This needs a tiny final step.

We invoke Poincaré duality: A cohomology class in $[\omega] \in H^p(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ is zero if and only the value of the pairing with any class $[\omega_2] \in H^{d-p}_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}_\lambda}^\vee)$

is zero. But the (absolute) value $[\omega] \cup [\omega_2]$ of the cup product can be given by an integral (See Prop.8.1.2). Therefore it can be estimated by the norm $< \omega - d\psi, \omega - d\psi >$ (Cauchy-Schwarz inequality) and hence must be zero. □

As usual we denote by $\widehat{G(\mathbb{R})}$ the unitary spectrum, for us it is simply the set of unitary irreducible representations of $G(\mathbb{R})$. Given $\tilde{\mathcal{M}}_\lambda$, we define

$$\mathrm{Coh}(\lambda) = \{\pi_\infty \in \widehat{G(\mathbb{R})} |\ H^\bullet(\mathfrak{g}, K_\infty, H_{\pi_\infty} \otimes \tilde{\mathcal{M}}_\lambda) \neq 0\}.$$

The theorem of Harish-Chandra says that this set is finite.

Let

$$H_{\mathrm{Coh}(\lambda)} = \bigoplus_{\pi:\pi_\infty \in \mathrm{Coh}(\lambda)} L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)(\pi_\infty \times \pi_f),$$

the theorem of Gelfand-Graev and Langlands assert that this is a finite sum of irreducible modules. This space decomposes again into $H^{\mathrm{cusp}}_{\mathrm{Coh}(\lambda)} \oplus H^{\mathrm{res}}_{\mathrm{Coh}(\lambda)}$

Then we get

Theorem (Borel, Garland, Matsushima-Murakami)

a)The map

$$H^\bullet(\mathfrak{g}, K_\infty, H^{(K_\infty)}_{\mathrm{Coh}(\lambda)} \otimes \mathcal{M}_\lambda) = \ Hom_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), H^{(K_\infty)}_{\mathrm{Coh}(\lambda)} \otimes \mathcal{M}_\lambda) \to H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$$

surjective. Especially the image contains $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$.

b) (Borel) The homomorphism

$$H^\bullet(\mathfrak{g}, K_\infty, H^{(\mathrm{cusp},\mathrm{K}_\infty)}_{\mathrm{Coh}(\lambda)} \otimes \mathcal{M}_\lambda) \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$$

is injective.

[Bo-Ga] Prop.5.6, they do not consider the above space $H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ we added an $\epsilon > 0$ to this proposition by claiming that this space is the image.

In general the homomorphism

$$H^\bullet(\mathfrak{g}, K_\infty, H^{\mathrm{res}}_{\mathrm{res}(\lambda)}, K_\infty) \otimes \mathcal{M}_\lambda) \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$$

is not injective. We come to this issue in the next section.

If we denote by $H^\bullet_{\mathrm{cusp}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ the image of the homomorphism in b), then we get a filtration of the cohomology by four subspaces

$$H^\bullet_{\mathrm{cusp}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \subset H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \subset H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \subset H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda). \quad (8.22)$$

We want to point out that our space $H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ is not the space denoted by the same symbol in the paper [Bo-Ca]. They define L^2 cohomology as the complex of square integrable forms, i.e. ω and $d\omega$ have to be square integrable. But then a closed form ω which is in L^2 gives the trivial class in their cohomology if we can write $\omega = d\psi$ where ψ must also be square integrable. In our definition we do not have that restriction on ψ.

A formula for the Poincaré duality pairing

We assume that $-w_0(\lambda) = c(\lambda)$. We have the positive definite hermitian scalar product on $\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), H^{(K_\infty)}_{\mathrm{Coh}(\lambda)} \otimes \mathcal{M}_\lambda)$ (See(8.5)). On the other hand we have the Poincaré duality pairing

$$H^i_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)(\omega_f) \times H^{d-i}_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee})(\omega_{1,f}) \to \mathbb{C} \tag{8.23}$$

where $\omega_f \cdot \omega_{1,f} = 1$. To relate these two products we recall the Hodge $*$-operator. (See for instance Vol. I. 4.11) This operator yields an isomorphism

$$\begin{aligned} * :\ &\mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda) \xrightarrow{\sim} \\ &\mathrm{Hom}_{K_\infty}(\Lambda^{d-p}(\mathfrak{g}/\mathfrak{k}), \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_{c\lambda}) \end{aligned} \tag{8.24}$$

We can use the $*$ operator to define the adjoint $\delta = (-1)^{d(p+1)+1} * d*$ and hence the Laplacian Δ (See (8.6). Especially the $*$ operator yields an identification between the $\mathcal{C}_\infty$-functions and the $\mathcal{C}_\infty$ differential forms in top degree.

We consider two differential forms

$$\omega_1, \omega_2 \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), \mathcal{C}^2_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda)$$

which are square integrable, then we defined the scalar product (See(8.5) $<\omega_1, \omega_2>$ of these two forms. By definition this scalar product is an integral over a function

$$<\omega_1, \omega_2> = \int_{\mathcal{S}^G_{K_f}} \{\omega_1, \omega_2\}.$$

If we have two closed forms $\omega_1 \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), \mathcal{C}^2_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda), \omega_2 \in \mathrm{Hom}_{K_\infty}(\Lambda^{d-p}(\mathfrak{g}/\mathfrak{k}), \mathcal{C}^2_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_{\lambda^\vee})$ and if one of these forms has compact support -say ω_2-then they define cohomology classes $[\omega_1] \in H^p(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda), [\omega_2] \in H^{d-p}_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda^\vee})$ and the cup product $[\omega_1 \cup [\omega_2]$ is defined and given by an integral (See proposition 8.1.2) over a form in top degree. Now we check easily - and this is the way how the $*$ operator is designed that for $\omega_1, \omega_2 \in \mathrm{Hom}_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), \mathcal{C}^2_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \otimes \mathcal{M}_\lambda)$ the integrand

$$\{\omega_1, \omega_2\} = <\omega_1 \wedge *\omega_2> .$$

Now we can formulate the

Proposition 8.1.4. *If $\omega_1, \omega_2 \in Hom_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), H^{(K_\infty)}_{\mathrm{Coh}(\lambda)} \otimes \mathcal{M}_\lambda)$ and if both classes $[\omega_1], [*\omega_2]$ are inner classes, i.e. can be represented by compactly supported forms then*

$$<\omega_1, \omega_2> = [\omega_1] \cup [*\omega_2]$$

Proof. Postponed We exploit the fact that we can construct a real valued $h : \mathcal{S}^G_{K_f} \to \mathbb{R}_{>0}$ □

This proposition is of course a consequences of Hodge theory if the quotient $\mathcal{S}^G_{K_f}$ is compact, but if this is not the case, then the assertion is delicate. In fact we have the standard example which shows that we need the assumption that both classes $[\omega_1], [*\omega_2]$ are inner. If take $\omega_1 = \omega_2$ to be the form in degree zero given by the constant function 1. Then the left hand side is non zero but the class $*1$ is the volume form which is trivial if $\mathcal{S}^G_{K_f}$ is not compact, and therefore the right hand side is not zero.

The proposition has the following nice corollary

Corollary 8.1.1. *If* $\omega \in \;\; Hom_{K_\infty}(\Lambda^p(\mathfrak{g}/\mathfrak{k}), H^{(K_\infty)}_{\mathrm{Coh}(\lambda)} \otimes \mathcal{M}_\lambda)$ *is non zero and if the restriction of* $*\omega$ *to the boundary is zero then* $[\omega] \neq 0$

Now we remember that in the previous sections we made the convention (See end of (8.1.1)) that our coefficient systems $\mathcal{M}_\lambda$ are $\mathbb{C}$ vector spaces. We now revoke this convention and recall that the coefficient systems $\mathcal{M}_\lambda$ should be replaced by $\mathcal{M}_\lambda \otimes_F \mathbb{C}$. Then in the above list (8.22) of four subspaces in the cohomology the second and the fourth subspace have a natural structure of F-vector spaces and they have a combinatorial definition, whereas the first and third subspace need some input from analysis in their definition. In other words if we replace $\mathcal{M}_\lambda$ in (8.22) by $\mathcal{M}_\lambda \otimes_f \mathbb{C}$ then the second and the fourth space can be written as

$$H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \otimes_F \mathbb{C} \subset H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \otimes_F \mathbb{C}$$

We believe that also the third space has a combinatorial definition, for this we need the weighted cohomology groups: *Weighted cohomology* ; G. Harder; R. MacPherson; M. Goresky Inventiones mathematicae (1994).

8.1.6 Consequences.

Vanishing theorems

If V is unitary and irreducible, then we have that $\bar{V} \xrightarrow{\sim} V^\vee$ and this implies for the central character

$$\overline{\chi_V(z)} = \chi_{V^\vee}(z) \text{ for all} z \in \mathfrak{Z}(\mathfrak{g}).$$

Combining this with Wigner's lemma we can conclude

If V *is an irreducible unitary* $(\mathfrak{g}, K_\infty)$*-module,* $\mathcal{M}_\lambda$ *is an irreducible rational representation, and if*

$$H^\bullet(\mathfrak{g}, K_\infty, V \otimes \mathcal{M}_\lambda) \neq 0$$

then $\chi_{\mathcal{M}_\lambda^\vee}(z) = \chi_{\mathcal{M}_\lambda}({}^tz) = \chi_{\bar{\mathcal{M}}_\lambda}(z)$

In other words: For an unitary irreducible $(\mathfrak{g}, K_\infty)$*-module* V *the cohomology with coefficients in an irreducible rational representation* $\mathcal{M}$ *vanishes, unless we have* $\mathcal{M}_\lambda^\vee \xrightarrow{\sim} \bar{\mathcal{M}}_\lambda$*, or in terms of highest weights unless* $-w_0(\lambda) = c(\lambda)$. (See 3.1.1)

If we combine this with the considerations following Wigner's lemma we get

Corollary *If* $\mathcal{M}$ *is an absolutely irreducible rational representation and if* $\mathcal{M}_\lambda^\vee$ *is not isomorphic to* $\bar{\mathcal{M}}_\lambda$ *then*

$$H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) = 0.$$

Hence also

$$H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) = 0.$$

We will discuss examples for this in section 8.1.6

The group $G/\mathbb{Q} = \mathbf{Sl}_2/\mathbb{Q}$

Let us consider the group $G/\mathbb{Q} = \mathrm{Sl}_2/\mathbb{Q}$. We have tautological representation $\mathrm{Sl}_2 \hookrightarrow \mathrm{Gl}(\mathbb{Q}^2) = \mathrm{Gl}(V)$ and we get all irreducible representations of we take the symmetric powers $\mathcal{M}_n = \mathrm{Sym}^n(V)$ of V. (See 2, these are the $\mathcal{M}_n[m]$ restricted to Sl_2, then the m drops out.)

In this case the Vogan-Zuckerman list is very short. It is discussed in [Slzwei] for the groups $\mathrm{Sl}_2(\mathbb{R})$ and $\mathrm{Sl}_2(\mathbb{C})$, where both groups are considered as real Lie-groups.

In the case $\mathrm{Sl}_2(\mathbb{R})$ we have the trivial module $\mathbb{C}$ and for any integer $k \geq 2$ we have two irreducible unitarizable $(\mathfrak{g}, K_\infty)$-modules $\mathcal{D}_k^\pm$ (the discrete series representations) (See [Slzwei], 4.1.5). These are the only $(\mathfrak{g}, K_\infty)$-modules which have non trivial cohomology with coefficients in a rational representation. If we now pick one of our rational representation $\mathcal{M}_n$, then the non vanishing cohomology groups are

$$H^q(\mathfrak{g}, K_\infty, \mathcal{M}_n \otimes \mathbb{C}) = \mathbb{C} \text{ for } l = 0, q = 0, 2$$

$$H^q(\mathfrak{g}, K_\infty, \mathcal{D}_k^\pm \otimes \mathcal{M}_n \otimes \mathbb{C}) = \mathbb{C} \text{ for } l = k-2, q = 1$$

The trivial $(\mathfrak{g}, K_\infty)$-module $\mathbb{C}$ occurs with multiplicity one in $L^2(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f)$ hence we get for the trivial coefficient system a contribution

$$H^\bullet(\mathfrak{g}, K_\infty, \mathbb{C}\otimes\mathcal{M}_n\otimes\mathbb{C}) = H^0(\mathfrak{g}, K_\infty, \mathbb{C})\oplus H^2(\mathfrak{g}, K_\infty, \mathbb{C}) = \mathbb{C}\oplus\mathbb{C} \to H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \mathbb{C}).$$

This map is injective in degree 0 and zero in degree 2.

For the modules $\mathcal{D}_k^\pm$ we have to determine the multiplicities $m^\pm(k)$ of these modules in the discrete spectrum of $L^2(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f)$. A simple argument using complex conjugation tells us $m^+(k) = m^-(k)$ Now we have the fundamental observation made by Gelfand and Graev, which links representation theory to automorphic forms:

We have an isomorphism

$$Hom_{\mathfrak{g},K_\infty}(\mathcal{D}_k^+, L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f) \xrightarrow{\sim} S_k(G(\mathbb{Q})\backslash \mathbb{H} \times G(\mathbb{A}_f)/K_f) =$$

$$\textit{space of holomorphic cusp forms of weight } k \textit{ and level } K_f$$

This is also explained in [Slzwei] on the pages following 23. We explain how we get starting from a holomorphic cusp form f of weight k an inclusion

$$\Phi_f : \mathcal{D}_k^+ \hookrightarrow L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f)$$

and that this map $f \mapsto \Phi_f$ establishes the above isomorphim. This gives us the famous Eichler-Shimura isomorphism

$$S_k(G(\mathbb{Q})\backslash \mathbb{H} \times G(\mathbb{A}_f)/K_f) \oplus \overline{S_k(G(\mathbb{Q})\backslash \mathbb{H} \times G(\mathbb{A}_f)/K_f)} \xrightarrow{\sim} H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{k-2}).$$

The group $G/\mathbb{Q} = R_{F/\mathbb{Q}}(\mathbf{Sl}_2/F)$.

For any finite extension $F/\mathbb{Q}$ we may consider the base restriction $G/\mathbb{Q} = R_{F/\mathbb{Q}}(Sl_2/F)$. (See Chap-II. 1.1.1). Here we want to consider the special case the $F/\mathbb{Q}$ is imaginary quadratic. In this case we have $G\otimes\mathbb{C} = \mathrm{Sl}_2\times\mathrm{Sl}_2/\mathbb{C}$ the factors correspond to the two embeddings of F into $\mathbb{C}$. The rational irreducible representations are tensor products of irreducible representations of the two factors $\mathcal{M}_\lambda = \mathcal{M}_{k_1}\otimes\mathcal{M}_{k_2}$ where again $\mathcal{M}_k = \mathrm{Sym}^k(\mathbb{C}^2)$. These representations are defined over F.

In this case we discuss the Vogan-Zuckerman list in [Slzwei], here we want to discuss a particular aspect. We observe that

$$\mathcal{M}_\lambda^\vee \xrightarrow{\sim} \mathcal{M}_{k_1}\otimes\mathcal{M}_{k_2}, \bar{\mathcal{M}}_\lambda = \mathcal{M}_{k_2}\otimes\mathcal{M}_{k_1}$$

and hence our corollary above yields for any choice of K_f

$$H_!^\bullet(\mathcal{S}^G_{K_f},\mathcal{M}) = 0 \text{ if } k_1\neq k_2.$$

In Chapter II we discuss the special examples in low dimensions. We take $F=\mathbb{Q}[i]$ and $\Gamma = \mathrm{Sl}_2[\mathbb{Z}[i]]$ this amounts to taking the standard maximal compact subgroup $K_f = \mathrm{Sl}_2[\hat{\mathcal{O}}_F]$. If now for instance $k_1>0$ and $k_2=0$, then we get $H_!^\bullet(\mathcal{S}^G_{K_f},\mathcal{M}_\lambda)=0$. Hence we have by definition $H_!^\bullet(\mathcal{S}^G_{K_f},\mathcal{M}) = H^\bullet_{\mathrm{Eis}}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})$ and we have complete control over the Eisenstein- cohomology in this case. Hence we know the cohomology in this case if we apply the analytic methods.

On the other hand in Chapter II we have written an explicit complex of finite dimensional vector spaces, which computes the cohomology. It is not clear to me how we can read off this complex the structure of the cohomology groups.

We get another example where this phenomenon happens, if we consider the group $\mathrm{Sl}_n/\mathbb{Q}$ if $n>2$. In Chap. IV 1.2 we described the simple roots $\alpha_1,\alpha_2,\dots,\alpha_{n-1}$, accordingly we have the fundamental highest weights $\omega_1,\dots,\omega_{n-1}$. The element w_0 (See 8.1.1) has the effect of reversing the order of the weights. Hence we see that for $\lambda = \sum n_i\omega_i$ we have

$$H_!^\bullet(\mathcal{S}^G_{K_f},\mathcal{M}_\lambda) = 0$$

unless we have $-w_0(\lambda)=\lambda$ and this means $n_i = n_{n-1-i}$.

The algebraic K-theory of number fields

I briefly recall the definition of the K-groups of an algebraic number field $F/\mathbb{Q}$. We consider the group $\mathrm{Gl}_n(\mathrm{O}_F)$, it has a classifying space BG_n. We can pass to the limit $\lim\limits_{n\to\infty}\mathrm{Gl}_n(\mathrm{O}_F) = \mathrm{Gl}(\mathrm{O}_F) = G$ and let BG its classifying space. Quillen invented a procedure to modify this space to another space BG^+, whose fundamental group is now abelian, but which has the same homology and cohomology as BG. Then he defines the algebraic K-groups as

$$K_i(\mathrm{O}_F) = \pi_i(\mathrm{BG}^+).$$

The space is an H-space, this means that we have a multiplication $m: \mathrm{BG}^+\times\mathrm{BG}^+\to\mathrm{BG}^+$ which has a two sided identity element. Then we get a homomorphism $m^\bullet: H^\bullet(\mathrm{BG}^+,\mathbb{Z})\to H^\bullet(\mathrm{BG}^+\times\mathrm{BG}^+,\mathbb{Z})$ and if we tensorize by

$\mathbb{Q}$ and apply the Künneth-formula then we get the structure of a Hopf algebra on the Cohomology

$$m^\bullet : H^\bullet(\mathrm{BG}^+, \mathbb{Q}) \to H^\bullet(\mathrm{BG}^+, \mathbb{Q}) \otimes H^\bullet(\mathrm{BG}^+, \mathbb{Q})$$

Then a theorem of Milnor asserts that the rational homotopy groups

$$\pi_i(\mathrm{BG}^+) \otimes \mathbb{Q} = \ \mathrm{prim}(H^i(\mathrm{BG}, \mathbb{Q}),$$

where prim are the primitive elements, i.e. those elements $x \in H^i(\mathrm{BG}, \mathbb{Q})$ for which

I sketch a second application. We discuss the group $G = R_{F/\mathbb{Q}}(\mathrm{Gl}_n/F)$, where $F/\mathbb{Q}$ is an algebraic number field. the coefficient system $\tilde{\mathcal{M}}_\lambda = \mathbb{C}$ is trivial. In this case Borel, Garland and Hsiang have shown hat in low degrees $q \leq n/4$

$$H^q(\mathcal{S}^G_{K_f}, \mathbb{C}) = H^q_{(2)}\mathcal{S}^G_{K_f}, \mathbb{C}).$$

On the other hand it follows from the Vogan-Zuckerman classification, that the only irreducible unitary $(\mathfrak{g}, K_\infty)$ modules V, for which $H^q(\mathfrak{g}, K_\infty, V) \neq 0$ and $q \leq n/4$ are one dimensional.

Hence we see that in low degrees

$$H^q(\mathfrak{g}, K_\infty, \mathbb{C}) \to H^q(\mathcal{S}^G_{K_f}, \mathbb{C})$$

is an isomorphism (Injectivity requires some additional reasoning.)

On the other hand we have $H^q(\mathfrak{g}, K_\infty, \mathbb{C}) = \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathbb{C})$ and obviously this last complex is isomorphic to the complex $\Omega^\bullet(X)^{G(\mathbb{R})}$ of $G(\mathbb{R})$-invariant forms on the symmetric space $G(\mathbb{R})/K_\infty$. Our field has different embeddings $\tau : F \hookrightarrow \mathbb{C}$, the real embeddings factor through $\mathbb{R}$, they form the set S_∞^{real} and the pairs of may conjugate embeddings into $\mathbb{C}$ form the set S_∞^{comp} Then

$$X = \prod_{v \in S_\infty^{\mathrm{real}}} \mathrm{Sl}_n(\mathbb{R})/SO(n) \times \prod_{S_\infty^{\mathrm{comp}}} \mathrm{Sl}_n(\mathbb{C})/SU(n).$$

Now the complex $\Omega^\bullet(X)^{G(\mathbb{R})}$ of invariant differential forms (all differentials are zero) does not change if we replace the group

$$G(\mathbb{R}) = \prod_{v \in S_\infty^{\mathrm{real}}} \mathrm{Sl}_n(\mathbb{R}) \times \prod_{S_\infty^{\mathrm{comp}}} \mathrm{Sl}_n(\mathbb{C})$$

by its compact form $G_c(\mathbb{R})$ and then we get the complex of invariant forms on the compact twin of our symmetric space

$$X_c = \prod_{v \in S_\infty^{\mathrm{real}}} SU_n(\mathbb{R})/SO(n) \times \prod_{S_\infty^{\mathrm{comp}}} (SU(n) \times SU(n))/SU(n),$$

but then

$$\Omega(X_c)^{G_c(\mathbb{R})} = H^\bullet(X_c, \mathbb{C}).$$

The cohomology of the topological spaces like the one on the right hand side has been computed by Borel in the early days of his career.

If we let n tend to infinity, we can consider the limit of these cohomology groups, then the limit becomes a Hopf algebra and we can consider the primitive elements

The semi-simplicity of the inner cohomology

Now we assume again that our representation $\tilde{\mathcal{M}}_\lambda$ is defined over some number field F we consider it as a subfield of $\mathbb{C}$. In other word we have a representation $r : G \times F \to \mathrm{Gl}(\mathcal{M}_\lambda)$. We have defined $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$, this is a finite dimensional F-vector space and Theorem 2 in Chapter II asserts that this is a semi simple module under the Hecke algebra. This is now an easy consequence of our results above.

The module $H_1 \subset L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A}_f)/K_f)$ can also be decomposed into a finite direct sum of irreducible $G(\mathbb{R}) \times \mathcal{H}_{K_f}$ modules

$$H_1 = \bigoplus_{\pi_\infty \otimes \pi_f \in \hat{H}_1} (H_{\pi_\infty} \otimes H_{\pi_f})^{m_1(\pi_\infty \times \pi_f)},$$

this module is clearly semi-simple. Of course it is not a $(\mathfrak{g}, K_\infty)$-module, but we can restrict to the K_∞-finite vectors and get

$$H^\bullet(\mathfrak{g}, K_\infty, H_1^{(K_\infty)} \otimes \mathcal{M}_\lambda \otimes \mathbb{C}) = \bigoplus_{\pi_\infty \otimes \pi_f \in \hat{H}_1} (\, \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), H_{\pi_\infty} \otimes \mathcal{M}_{\mathbb{C}}) \otimes H_{\pi_f})^{m_1(\pi_\infty \times \pi_f)}$$

This is a decomposition of the left hand side into irreducible $\mathcal{H}_{K_f}$ modules. Now we have the surjective map

$$H^\bullet(\mathfrak{g}, K_\infty, H_1^{(K_\infty)} \otimes \mathcal{M}_\lambda \otimes \mathbb{C}) \to H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C})$$

hence it follows that $H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C}))$ is a semi simple $\mathcal{H}_{K_f}$ module and hence also $H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ is a semi simple $\mathcal{H}_{K_f}$ module.

At this point we encounter an interesting problem. We have the three subspaces (See end of 3.2)

$$H^\bullet_{\mathrm{cusp}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C}) \subset H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \otimes \mathbb{C} \subset H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C}) \subset H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \otimes \mathbb{C},$$

note the positions of the tensor symbol $\otimes$. The first and the third space are only defined after we tensorize the coefficient system by $\mathbb{C}$, whereas the second and the fourth cohomology groups by definition F vector spaces tensorized by $\mathbb{C}$.

Now the question is whether the first and the third space also have a natural F -vector space structure. Of course we get a positive answer, if the Manin-Drinfeld principle holds. All the vector spaces are of course modules under the Hecke algebra and we and we can look at their spectra

$$\begin{array}{cc} \Sigma(H^\bullet_{\mathrm{cusp}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C})) = \Sigma_{\mathrm{cusp}} & \Sigma(H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C})) = \Sigma_! \\ \Sigma(H^\bullet_{(2)}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C})) = \Sigma_{(2)} & \Sigma(H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C})) = \Sigma \end{array}.$$

If now for instance $\Sigma_{\mathrm{cusp}} \cap (\Sigma_! \setminus \Sigma_{\mathrm{cusp}} = \emptyset$ then we can define $H^\bullet_{\mathrm{cusp}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \subset H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ as the subspace which is the sum of the isotypical components in Σ_{cusp}.

If this is the case we say that the cuspidal cohomology is *intrinsically definable* and we get a canonical decomposition

$$H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) = H^\bullet_{\mathrm{cusp}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \oplus H^\bullet_{!,\mathrm{noncusp}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda).$$

The classical Manin-Drinfeld principle refers to the two spectra $\Sigma_! \subset \Sigma$, if it is true in this case we get a decomposition

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) = H^\bullet_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \oplus H^\bullet_{\mathrm{Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$$

the canonical complement is called the Eisenstein cohomology. (See Chap. II 2.2.3 and Chap III 5.)

8.1.7 Franke's Theorem

: ....

8.2 Modular symbols

8.2.1 The general pattern

We start from the following data. Let $H/\mathbb{Q}$ be a (reductive) subgroup of our group $G/\mathbb{Q}$. Let $K^{H,(1)}_\infty$ be the connected component of the identity of a maximal compact subgroup of $H(\mathbb{R})$ we put $X^H = H(\mathbb{R})/K^{H,(1)}_\infty$. We have the spaces

$$\mathcal{S}^G_{K_f} = G(\mathbb{Q})\backslash X \times G(\mathbb{A}_f)/K_f, \mathcal{S}^H_{K^H_f} = H(\mathbb{Q})\backslash X^H \times H(\mathbb{A}_f)/K_f.$$

From the inclusion $i : H \to G$ we get maps between these locally symmetric spaces

$$j(x, \underline{g}_f) : \mathcal{S}^H_{K^H_f} \to \mathcal{S}^G_{K_f}$$

which depend on the choice of "pin points" $(x, \underline{g}_f) \in X \times G(\mathbb{A}_f)$. These pin points have to be chosen with some care:

a) The point $x \in X$ can be viewed as a Cartan involution Θ_x on $G(\mathbb{R})$ and Θ_x should fix $H(\mathbb{R})$. Hence it is also a Cartan involution on H and we require that it is the identity on our chosen $K^{H,(1)}_\infty$. Let us denote this subset of X by $X^{(H,K^{H,(1)}_\infty)}$. Let N be the subgroup of the normalizer of $H/\mathbb{Q}$ which also normalizes $K^{H,(1)}_\infty$. Then $N(\mathbb{R})$ acts on $X^{(H,K^{H,(1)}_\infty)}$. I think that this action is transitive and the orbits under the group $N(\mathbb{R})^{(1)}$ are the connected components.

b)The element $\underline{g}_f$ has to satisfy a similar condition:

$$K^H_f \underline{g}_f K_f = \underline{g}_f K_f$$

(Recall that we always have make careful choices of the level if we deal with integral cohomology.)

Choosing $(x, \underline{g}_f)$ we get a map

$$j(x, \underline{g}_f) : H(\mathbb{Q})\backslash H(\mathbb{R})/K^H_\infty \times H(\mathbb{A}_f)/K^H_f \longrightarrow \mathcal{S}^G_{K_f}$$

which is defined by

$$(h_\infty, \underline{h}_f) \mapsto (h_\infty x, \underline{h}_f \underline{g}_f).$$

Now we assume that we have coefficient systems $\tilde{\mathcal{M}}_{\mathcal{O}}, \mathcal{O}_\mu$ coming from representations of $\rho : \mathbb{G}/\mathbb{Z} \to \mathrm{Gl}(\mathcal{M}_{\mathcal{O}})$ resp. a one dimensional representation $\mu : \mathcal{H}/\mathbb{Z} \to \mathbb{G}_m$. We assume that we also have a homomorphism from the restriction of ρ to $\mathcal{H}/\mathbb{Z}$ to μ, i.e

$$r_{\lambda,\mu} : \mathcal{M}_{\mathcal{O}} \to \mathcal{O}_\mu$$

which invariant under the action of $\mathcal{H}$. This induces a homomorphism of sheaves

$$r^*_{\lambda,\mu} : j(x, \underline{g}_f)^*(\tilde{\mathcal{M}}_{\mathcal{O}}) \to \tilde{\mathcal{O}}_\mu. \tag{8.25}$$

Then these data provide a homomorphism for the cohomology groups

$$j(x, \underline{g}_f)^\bullet : H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) \to H^\bullet(\mathcal{S}^H_{K^H_f}, \mathcal{O}_\mu)$$

We are interested in this homomorphism in degree $d_H = \dim \mathcal{S}^H_{K^H_f}$.

In this degree we know the compactly supported cohomology of $\mathcal{S}^H_{K^H_f}$

$$H^{d_H}_c(\mathcal{S}^H_{K^H_f}, \mathcal{O}_\mu) = H^{d_H}(\mathcal{S}^H_{K^H_f}, i_!(\tilde{\mathcal{O}})_\mu) = \bigoplus_\chi H^{d_H}(\mathcal{S}^H_{K^H_f}, i_!(\tilde{\mathcal{O}})_\mu)[\chi_f]$$

where we sum over characters $\tilde{\chi}_f$ of type μ. on $\pi_0(H(\mathbb{R})) \times H(\mathbb{A}_f)$ (See (6.3.4)) The eigenspaces are projective $\mathcal{O}$- modules of rank one let us assume that they are free and that we have chosen generators c_χ. We will call such generators modular symbols.

We see that the homomorphism $j(x, \underline{g}_f)^\bullet$ is not yet good enough it has the wrong target, if we want to evaluate cohomology classes on the fundamental cycles of $H^{d_H}(\mathcal{S}^H_{K^H_f}, i_!(\tilde{\mathcal{O}})_\mu)$. We need to modify the source.

We study the extension of $j(x, \underline{g}_f)$ to the compactification

$$\bar{j}(x, \underline{g}_f) : \bar{\mathcal{S}}^H_{K^H_f} \to \bar{\mathcal{S}}^G_{K_f}$$

We recall the construction of sheaves with intermediate support conditions (6.2.1.Let us assume that we can find a Σ such that the image of $\partial(\bar{\mathcal{S}}^H_{K^H_f})$ factors through $\partial_\Sigma(\bar{\mathcal{S}}^G_{K_f})$. Then our homomorphism r yields a homomorphism between sheaves (see (6.19))

$$r^!_{\lambda,\mu} : \bar{j}(x, \underline{g}_f)^*(i_{\Sigma,*,!}(\tilde{\mathcal{M}})) \to i_!(\tilde{\mathcal{O}}_\mu). \tag{8.26}$$

and hence we get a homomorphism in cohomology

$$\bar{j}((x, \underline{g}_f), r_{\lambda,\mu})^{d_H} : H^{d_H}(\mathcal{S}^G_{K_f}, i_{\Sigma,*,!}(\tilde{\mathcal{M}})) \to H^{d_H}(\mathcal{S}^H_{K^H_f}, i_!(\tilde{\mathcal{O}}_\mu)) \tag{8.27}$$

If we change x inside a connected component of $X^{(H,K^{H,(1)}_\infty)}$ then $\bar{j}((x, \underline{g}_f), r_{\lambda,\mu})^{d_H}$ does not change, and hence we can view x as a discrete variable.

We still have the variable $\underline{g}_f$. This has to satisfy the above condition b), it has to respect the level and we have to fix the level because we want to get integral cohomology groups. If we tensorize our coefficient systems with F (the quotient field of $\mathcal{O}$) then we can consider the limit

$$\lim_{K_f} H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F) = H^\bullet(\mathcal{S}^G, \tilde{\mathcal{M}}_F),$$

and this limit is now a $\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)$ module. Doing this also with $\mathcal{S}^H_{K^H_f}$ we can forget the constraint on $\underline{g}_f$ and we get an intertwining operator

$$\bar{j}((x,\underline{g}_f),r_{\lambda,\mu})^{d_H} : H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))_{\bar{\mathbb{Q}}}) \to H^{d_H}(\mathcal{S}^H, i_!(\bar{\mathbb{Q}}_\mu)) = \bigoplus_\chi \bar{\mathbb{Q}}[\tilde{\chi}_f] \tag{8.28}$$

where the direct sum on the right hand side is now infinite, we sum over all characters of type μ.

Assume that we have chosen a basis element $c_\chi \in H^{d_H}(\mathcal{S}^H, i_!(\bar{\mathbb{Q}}_\mu))[\chi]$ (a modular symbol) for all χ. For a class $\xi \in H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))_{\bar{\mathbb{Q}}})$ we get

$$\bar{j}((x,\underline{g}_f),r_{\lambda,\mu})^{d_H}(\xi) = \sum_\chi F_\chi(\xi,(x,\underline{g}_f))c_\chi \tag{8.29}$$

The cohomology $H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))_{\bar{\mathbb{Q}}})$ is a $\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)$-module.

Lemma 8.2.1. *We get get an intertwining operator between $\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)$-modules*

$$J_{c_\chi}(r_{\lambda,\mu}) : H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))) \to \; Ind_{\pi_0(H(\mathbb{R}))\times H(\mathbb{A}_f)}^{\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)} \tilde{\chi}_f^{-1}$$

The question arises to compute this operator. Of course it is not so clear what this means. First of all we have the problem that we do not know the left hand side. Recall that the left hand side still sits in an exact sequence

$$0 \to H^{d_H-1}(\partial_\pi(\mathcal{S}^G),\tilde{\mathcal{M}}_{\bar{\mathbb{Q}}}) \to H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))_{\bar{\mathbb{Q}}}) \to H^{d_H}_!(\mathcal{S}^G,\tilde{\mathcal{M}})_{\bar{\mathbb{Q}}}) \to 0.$$

We try to produce absolutely irreducible submodules

$$H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))_F)(\pi_f) \subset H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))_F$$

and restrict the intertwining operator to this submodule. Then we may be lucky and the space of $\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)$ homomorphisms of this submodule into $\mathrm{Ind}_{\pi_0(H(\mathbb{R}))\times H(\mathbb{A}_f)}^{\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)}\tilde{\chi}_f^{-1}$ is one dimensional and contains some kind of canonical generator . In this case the intertwining operator is essentially given by a number

1) We may, of course, consider first the boundary map

$$H^{d_H-1}(\partial\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}}) \longrightarrow H^{d_H}_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}}),$$

and restrict the map J_{c_χ} to its image.

If we want to understand this restriction – perhaps we should simply denote it by ∂J_{c_χ} – then we have to look at the image of c_χ under the boundary map

$$\begin{array}{cccc} \partial & : & H_{d_H}(\mathcal{S}^H_{K^H_f},\partial\mathcal{S}^H_{K^H_f},\tilde{\mathcal{M}}_{\mathcal{O}}) & \longrightarrow & H_{d_H-1}(\partial\mathcal{S}^H_{K^H_f},\tilde{\mathcal{M}}_{\mathcal{O}}) \\ & & & & \downarrow j(x,\underline{g}_f) \\ & & & & H_{d_H-1}(\partial\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}}). \end{array}$$

I think this restriction is not so interesting, since we are basically dealing with a smaller group.

In certain cases it happens that

$$j(x,\underline{g}_f)(\partial c_\chi)=0 \tag{M_1}$$

If this condition is satisfied, then we know that J_{c_χ} factorizes over

$$J_{c_\chi}: H_!^{d_H}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}}) \longrightarrow \operatorname{Ind}_{\tilde{H}(\mathbb{A}_f)}^{\tilde{G}(\mathbb{A}_f)} \tilde{\chi}_f^{-1}.$$

If this is the case we are somewhat better off, because cohomology classes in $H_!^{d_H}(\mathcal{S}^G_{K_f},\mathcal{M}_{\mathbb{C}})$ can be constructed and described using automorphic forms (Θ-series or Fourier expansions (See 2.2.2).) Moreover we know that after tensorization with the quotient field F of $\mathcal{O}$ the inner cohomology becomes semi simple and we can restrict J_{c_χ} to isotypical submodules. (See next section)

Of course we are always in this special case it the group $H/\mathbb{Q}$ is anisotropic, because in this case $j(x,\underline{g}_f)\in H_c^{d-d_H}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)=H_{d_H}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}})$.

In this case we may even pair $j(x,\underline{g}_f)$ with elements in $H^{d_H}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}})$

2) Another condition that may be satisfied is the Manin-Drinfeld principle, i.e. we have an isotypical decomposition

$$H^{d_H}_{\mathrm{Eis}}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F)\oplus H_!^{d_H}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F). \tag{M_2}$$

Then we may restrict J_{c_χ} to the second summand. We get

$$J_{c_\chi,!}: H_!^{d_H}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_F) \longrightarrow \operatorname{Ind}_{\tilde{H}(\mathbb{A}_f)}^{\tilde{G}(\mathbb{A}_f)} \tilde{\chi}_f.$$

3)

Model spaces

I want to introduce some abstract concept of the production of cohomology classes and the evaluation of these intertwining operators on these classes. To do this we introduce model spaces.

We assume that we have a family of local smooth and admissible representations $\{X_{\pi_v}\}$ where v runs over all places. For almost all finite places p the representation $\{X_{\pi_p}\}$ should be an unramified irreducible principal series representation. We assume that X_{π_∞} is an irreducible Harish-Chandra module with non trivial cohomology $H^\bullet(\mathfrak{g},K_\infty,X_{\pi_\infty}\otimes\mathcal{M}_{\mathbb{C}})\neq 0$. Furthermore we assume that we have an intertwining operator of $(\mathfrak{g},K_\infty)\times G(\mathbb{A}_f)$-modules

$$\Phi: X_{\pi_\infty}\otimes\bigotimes_p X_{\pi_p}\longrightarrow \mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A})).$$

This induces of course an intertwining operator

$$\begin{aligned} H^\bullet(\mathfrak{g},K_\infty,X_{\pi_\infty}\otimes\mathcal{M}_{\mathbb{C}})\otimes\textstyle\bigotimes_p X_{\pi_p} &\xrightarrow{\Phi^\bullet} H^\bullet(\mathfrak{g},K_\infty,\mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A}))\otimes\mathcal{M}_{\mathbb{C}})\\ &= H^\bullet(\mathcal{S}^G,\tilde{\mathcal{M}}_{\mathbb{C}})\end{aligned}$$

We introduce a subspace of $\mathcal{C}_\infty(G(\mathbb{Q})\backslash G(\mathbb{A}))$. We consider the subspace of functions of moderate growth and inside this space we consider the space of functions which are cuspidal along the strata $\partial_P(\mathcal{S}^G)$ for the parabolic subgroups $P \in \Sigma$, i.e. which satisfy

$$\int_{U_P(\mathbb{Q})\backslash U_P(\mathbb{A})} f(\underline{u}g)d\underline{u} \equiv 0$$

for these parabolic subgroups. Let us call this subspace $\mathcal{C}_\infty^{(\Sigma)}(G(\mathbb{Q})\backslash G(\mathbb{A}))$. We assume that our intertwining operator factors through the subspace of Σ cuspidal functions

$$\Phi : X_{\pi_\infty} \otimes \bigotimes_p X_{\pi_p} \longrightarrow \mathcal{C}_\infty^{(\Sigma)}(G(\mathbb{Q})\backslash G(\mathbb{A})) \tag{8.30}$$

and we assume in addition that we have multiplicity one, this means that Φ is unique up to scalar.

We have an action of $\pi_0(G(\mathbb{R}))$ on $H^\bullet(\mathfrak{g}, K_\infty, X_{\pi_\infty} \otimes \mathcal{M}_\mathbb{C})$ let $\epsilon : \pi_0(G(\mathbb{R})) \to \{\pm 1\}$ be a character and let ω_ϵ be a differential form representing an eigenclass $[\omega_\epsilon]$. In [Ha-Gl2] we explain how a Hecke character χ_f extends to a character $\tilde{\chi}_f : \pi_0(H(\mathbb{R}))H(\mathbb{A}_f) \to \{\pm 1\}$. We have the homomorphism $\pi_0(H(\mathbb{R})) \to \pi_0(G(\mathbb{R}))$ and we require that $\chi_\infty = \epsilon_\infty$

We get a diagram

$$\begin{array}{lcr}
H^\bullet(\mathfrak{g}, K_\infty, X_{\pi_\infty} \otimes \mathcal{M}_\mathbb{C})(\epsilon_\infty) \otimes \otimes_p X_{\pi_p} & & \\
\qquad\qquad \downarrow \Phi^{d_H} & & \\
H^{d_H}(\mathfrak{g}, K_\infty, \mathcal{C}_\infty^{(\Sigma)}(G(\mathbb{Q})\backslash G(\mathbb{A})) \otimes \mathcal{M}_\mathbb{C}) & \xrightarrow{\Phi^{d_H,\Sigma}} & H^{d_H}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \otimes \mathbb{C} \\
 & & \uparrow i_\Sigma^{d_H} \otimes \mathbb{C} \\
\mathrm{Ind}_{\pi_0(H(\mathbb{R}))\times H(\mathbb{A}_f)}^{\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)} \tilde{\chi}_f^{-1} \otimes \mathbb{C} & \xleftarrow{J_{c_\chi}} & H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))) \otimes \mathbb{C}
\end{array}$$

Proposition 8.2.1. *The image of Φ^{d_H} is contained in the image of $i_\Sigma^{d_H} \otimes \mathbb{C}$*

Proof. Careful analysis using reduction theory □

We now make the further assumption that the Manin-Drinfeld principle is valid for the image $H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ of $i_\Sigma^{d_H}$, this means that we have unique $G(\mathbb{A}_f)$-invariant section

$$s_\Sigma^{d_H} : H^{d_H}_{\Sigma,!}(\mathcal{S}^G, \tilde{\mathcal{M}}) \to H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))) \tag{8.31}$$

Then we get an arrow

$$H^{d_H}(\mathfrak{g}, K_\infty, \mathcal{C}_\infty^{(\Sigma)}(G(\mathbb{Q})\backslash G(\mathbb{A})) \otimes \mathcal{M}_\mathbb{C}) \to \mathrm{Ind}_{\pi_0(H(\mathbb{R}))\times H(\mathbb{A}_f)}^{\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)} \tilde{\chi}_f^{-1} \otimes \mathbb{C}$$

which should be placed into the middle of the above diagram. The cohomology on the left hand side can by computed by the de-Rham complex.

Theorem 8.2.1. *This arrow is given by the integral*

$$J_{c_\chi}(\xi)((x,\underline{g}_f),r_{\lambda,\mu})([\omega]) = \int_{\mathcal{S}^H_{K^H_f}} r_{\lambda,\mu}(j^*(x,\underline{g}_f)(\omega))$$

We can take the composition

$$\Phi^{d_H}: H^{d_H}(\mathfrak{g},K_\infty,\pi_\infty\otimes\mathcal{M}_\mathbb{C})(\epsilon_\infty)\otimes\bigotimes_p X_{\pi_p} \longrightarrow H^{d_H}_!(\mathcal{S}^G,\tilde{\mathcal{M}}_\mathbb{C}) \xrightarrow{J_{c_\chi,!}} \mathrm{Ind}_{\tilde{H}(\mathbb{A}_f)}^{\tilde{G}(\mathbb{A}_f)}\tilde{\chi}_f^{-1}$$

Let us pick a form in the ε-eigenspace

$$\omega_\varepsilon \in \mathrm{Hom}_{K_\infty}(\Lambda^{d_H}(\mathfrak{g}/\mathfrak{k}),\pi_\infty\otimes\tilde{\mathcal{M}}_\mathbb{C})$$

and let us assume that the restriction of ε to $\pi_0(H(\mathbb{R}))$ is the infinity component of $\tilde{\chi}$. Then we get a new intertwining operator

$$J_{c_\chi,!}(\omega_\varepsilon):\bigotimes_p X_{\pi_p} \longrightarrow \mathrm{Ind}_{H(\mathbb{A}_f)}^{G(\mathbb{A}_f)}\chi_f^{-1}$$

which is defined by

$$J_{c_\chi,!}(\omega_\varepsilon)(\psi_f) = J_{c_\chi,!}\circ\Phi^{d_H}(\omega_\varepsilon\otimes\psi_f)].$$

Again we have the problem to compute this operator. The situation has changed. The source and the target of $J_{c_\chi,!}\circ\Phi^{d_H}$ are restricted tensor products of local representations. A necessary condition for $J_{c_\chi,!}\circ\Phi^{d_H}\neq 0$ is that for all primes p the vector space

$$\mathrm{Hom}_{G(\mathbb{Q}_p)}(X_{\pi_p},\ \mathrm{Ind}_{H(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)}\chi_p^{-1})\neq 0. \qquad (I_p)$$

Therefore we assume that this condition is fulfilled. There are cases where the above condition is not always true, see for instance the Hilbert modular surfaces [H-L-R].

If the local condition (I_p) is satisfied for all primes p, then we have interesting special cases where

$$\dim\ \mathrm{Hom}_{G(\mathbb{Q}_p)}(X_{\pi_p},\ \mathrm{Ind}_{H(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)}\chi_p^{-1}) = 1 \qquad (I_{pp})$$

Let us assume that the representations X_{π_p} are somehow given to us as very concrete representations and (I_{pp}) is true for all primes p. Then it may be possible to select at each prime p a natural generator

$$I^{\mathrm{loc}}_{\chi_p}\in\ \mathrm{Hom}_{G(\mathbb{Q}_p)}(X_{\pi_p},\ \mathrm{Ind}_{H(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)}\chi_p^{-1}).$$

(This will be discussed in our examples.) We can define

$$I^{\mathrm{loc}}_{\chi_f} = \bigotimes_p I^{\mathrm{loc}}_{\chi_p}\in\ \mathrm{Hom}_{G(\mathbb{A}_f)}(\bigotimes_p X_{\pi_p},\ \mathrm{Ind}_{H(\mathbb{A}_f)}^{G(\mathbb{Q}_p)}\chi_f^{-1})$$

and now we can formulate the following question:

The operator $J_{c_\chi,!}(\omega_\epsilon)$ is a multiple of the product of local operators, the problem arises to compute the proportionality factor in

$$J_{c_\chi,!}(\omega_\epsilon) = \mathcal{L}(\pi_f,\chi)\cdot I^{loc}_{\chi_f}.$$

The general idea is that this proportionaly factor is related to a special value of an L-function attached to $\bigotimes_v \pi_v$.

8.2.2 Rationality and integrality results

We assume that we have fixed a finite level. We assume that the Manin-Drinfeld principle (8.31) is valid we get a decomposition up to isogeny

$$H^{d_H-1}(\partial(\mathcal{S}^G_{K_f}), \tilde{\mathcal{M}}) \oplus H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) \subset H^{d_H}(\mathcal{S}^G_{K_f}, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))). \tag{8.32}$$

An absolutely irreducible isotypical submodule $H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_F(\pi_f) \subset H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_F$ can also be viewed as a submodule in $H^{d_H}(\mathcal{S}^G_{K_f}, i_{\Sigma,*,!}(\tilde{\mathcal{M}})_F))$.

We intersect $H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_F(\pi_f)$ with the integral cohomology $H^{d_H}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})$ and get the submodule $H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}}(\pi_f) \subset H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_{\mathcal{O}_F})_{\text{ int}}$. The same procedure gives us a submodule

$$H^{d_H}(\mathcal{S}^G_{K_f}, i_{\Sigma,*,!}(\tilde{\mathcal{M}}_{\mathcal{O}_F}))_{\text{ int}}(\pi_f) \subset H^{d_H}(\mathcal{S}^G_{K_f}, i_{\Sigma,*,!}(\tilde{\mathcal{M}}_{\mathcal{O}_F}))_{\text{ int}} \tag{8.33}$$

The map

$$r_{\Sigma,!}: H^{d_H}(\mathcal{S}^G_{K_f}, i_{\Sigma,*,!}(\tilde{\mathcal{M}}))_{\mathcal{O}_F})_{\text{ int}}(\pi_f) \to H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}}(\pi_f) \tag{8.34}$$

becomes an isomorphism if we tensorize it by F and hence the image of this map is a submodule of finite index. We define

$$\Delta(\pi_f) = [H^{d_H}_{\Sigma,!}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\text{ int}}(\pi_f) : r_{\Sigma,!}(H^{d_H}(\mathcal{S}^G_{K_f}, i_{\Sigma,*,!}(\tilde{\mathcal{M}})_{\mathcal{O}_F})_{\text{ int}}(\pi_f))] \tag{8.35}$$

We return to our model space and assume that we have multiplicity one (8.30). Our isotypical subspace in (8.33) is defined over the field F. We now assume that all the local components X_{π_p} are defined over F, i.e. the local representations are defined over F. Then we get for any embedding $\sigma : F \to \mathbb{C}$ an isomorphism

$$\Phi^H_\sigma(\omega_\epsilon) : (\bigotimes_p X_{\pi_p}) \otimes_\sigma \mathbb{C}) \to H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}_F))(\pi_f \times \epsilon_\infty) \otimes_\sigma \mathbb{C} \tag{8.36}$$

these are isomorphisms over $\mathbb{C}$ between absolutely irreducible $G(\mathbb{A}_f)$ modules which are defined over F. Hence we can find numbers (the periods) $\Omega(\pi_f \times \epsilon, \sigma) \in \mathbb{C}^\times$ such that

$$\frac{\Phi^H_\sigma(\omega_\epsilon)}{\Omega(\pi_f \times \epsilon, \sigma)} : \bigotimes_p X_{\pi_p} \xrightarrow{\sim} H^{d_H}(\mathcal{S}^G, i_{\Sigma,*,!}(\tilde{\mathcal{M}}_F))(\pi_f \times \epsilon_\infty) \tag{8.37}$$

is an isomorphism over F. We can choose these periods consistent with the action of the Galois group and then it becomes clear that these period arrays are unique up to an element in $F^\times$.

We may also assume that after fixing a level we have an integral structure on our model space, i.e we have lattices $X^{K_p}_{\pi_p,\mathcal{O}_F}$ which are modules under the

Hecke algebra. If we invert some primes and pass to $\mathcal{O}_F[\frac{1}{N}]$ then we can arrange our periods in such a way that

$$\frac{\Phi^H_\sigma(\omega_\epsilon)}{\Omega(\pi_f\times\epsilon,\sigma)}:(\bigotimes_p X^{K_p}_{\pi_p,\mathcal{O}_F}\otimes\mathcal{O}_F[\frac{1}{N}])\xrightarrow{\sim} H^{d_H}(\mathcal{S}^G_{K_f},i_{\Sigma,*,!}(\tilde{\mathcal{M}}_{\mathcal{O}_F}))_{\text{ int}}(\pi_f\times\epsilon_\infty)\otimes\mathcal{O}_F[\frac{1}{N}]) \tag{8.38}$$

This pins down the periods up to an element in $\mathcal{O}_F[\frac{1}{N}]^\times$.

We get a formula

$$j((x,\underline{g}_f),r_{\lambda,\mu})(\Phi^{d_H}(\frac{[\omega_\epsilon]}{\Omega(\pi_f,\omega_\epsilon)}\times\psi_f))=\frac{\mathcal{L}(\pi\otimes\chi,\mu)}{\Omega(\pi_f,\omega_\epsilon)}I^{\text{loc}}_{\chi_f}(\psi_f)(\underline{g}_f)c_\chi \tag{8.39}$$

By definition of the expression $\Phi^{d_H}(\frac{[\omega_\epsilon]}{\Omega(\pi_f,\omega_\epsilon)}\times\psi_f)$the left hand side is rational if $\psi_f\in\bigotimes_p X_{\pi_p,F}$ and we get a rationality statement for the value of the L-function provided we know that $I^{\text{loc}}_{\chi_f}(\psi_f)(\underline{g}_f)$ is non zero and in F.

We have to choose $\psi_f\in\bigotimes_p X^{K_p}_{\mathcal{O}_F[\frac{1}{N}]}$, and we choose $\underline{g}_f$ such that $K^H_f\underline{g}_fK_f=\underline{g}_fK_f)$). The first choice provides an integral cohomology class in $H^{d_H}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathcal{O}_F[\frac{1}{N}]})(\pi_f)$. But this class is not necessarily the image of an integral class under $r_{\Sigma,!}$ this will be the case if we multiply it with $\Delta(\pi_f)$. Once we have done this we get that

$$j((x,\underline{g}_f),r_{\lambda,\mu})(\Phi^{d_H}(\frac{[\omega_\epsilon]}{\Omega(\pi_f,\omega_\epsilon)}\times\Delta(\pi_f)\psi_f))=\Delta(\pi_f)\frac{\mathcal{L}(\pi\otimes\chi,\mu)}{\Omega(\pi_f,\omega_\epsilon)}I^{\text{loc}}_{\chi_f}(\psi_f)(\underline{g}_f)c_\chi \tag{8.40}$$

is a number in $\mathcal{O}_F[\frac{1}{N}]$.

Then we have to optimize the choice of $\underline{g}_f$, this means that we have to keep the numerator of $I^{\text{loc}}_{\chi_f}(\psi_f)(\underline{g}_f)$ small. Then we get an integrality result for the L-value.

We discuss this in the next example.

8.2.3 The special case Gl_2

We consider the special case $G=Gl_2/\mathbb{Q}$. In this case we have very nice model spaces, namely the Whittaker model, our map Φ is given by the Fourier expansion and the theory of the Kirillow-model gives us a canonical choice for the local intertwining operators. Let $\mathcal{M}_n$ be the $\mathbb{Q}$-vector space of homogeneous polynomials $P(X,Y)$ of degree n and with coefficients in $\mathbb{Q}$. An element $\gamma=\begin{pmatrix}a&b\\c&d\end{pmatrix}$ acts by $(\gamma P)(X,Y)=P(aX+cY,bX+dY)$. Sometimes we twist this action by a power of the determinant $\det(\gamma)^r$, then the module is denoted by $\mathcal{M}_n[r]$. From now on $\mathcal{M}$ will be one of the modules $\mathcal{M}_n[r]$, i.e. our highest weight will be the pair $\lambda=(n,r)$. The subgroup which provides the modular symbols will be our standard maximal torus T and the $r_{\lambda,\mu}$ will be the projections to $X^{n-\mu}Y^\mu$.

We assume that a K_f is been chosen. Let us assume that we selected a K_f stable lattice $\tilde{\mathcal{M}}_{\mathbb{Z}}$ and we consider the exact sequence of modules under the Hecke algebra

$$\to H^0(\partial\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathbb{Z}}) \to H^1_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathbb{Z}}) \to H^1(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathbb{Z}}) \to H^1(\partial\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\mathbb{Z}}).$$

We can tensorize our sequence by $\mathbb{Q}$, and then in this case the Manin-Drinfeld principle is valid

$$H^1_c(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}) = H^1_{\mathrm{Eis}}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})) \oplus H^1_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}).$$

The first summand can be described in terms of induced representations

$$H^0(\partial\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})\otimes\overline{\mathbb{Q}} = \bigoplus_{\chi:\ \mathrm{type}(\chi)=\lambda} \left(\ \mathrm{Ind}_{\tilde{B}(\mathbb{A})}^{\tilde{G}(\mathbb{A})}\tilde{\chi}\right)^{K_f}$$

where λ is the highest weight of our module, where χ runs over the Hecke characters with some restriction conditions dictated by K_f, and where $\tilde{\chi}$ is the character on $\pi_0(T(\mathbb{R}))\times T(\mathbb{A}_f)$ attached to it (see [GL_2], ...).

The module $H^1_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})$ is semisimple, if we tensorize by $\overline{\mathbb{Q}}$, then we get an isotypical decomposition

$$H^1_!(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\overline{\mathbb{Q}}}) = \bigoplus_{\pi_f} H^1(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\overline{\mathbb{Q}}})(\pi_f)$$

where π_f is an isomorphism class of a (finite dimensional) $\overline{\mathbb{Q}}$-vector space with an irreducible action of $\mathcal{H}$ on it. Since we fixed the level we have only finitely many of them. The Galois action on $\overline{\mathbb{Q}}$ induces a permutation of the π_f, if $\sigma\in\ \mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$, then we can define the isomorphism class π_f^σ. It is clear that we have a finite extension $\mathbb{Q}(\pi_f)\subset\overline{\mathbb{Q}}$ such that $\pi_f^\sigma=\pi_f$ for all $\sigma\in\ \mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}(\pi_f))$. The field $\mathbb{Q}(\pi_f)$ is the field of definition of the representation π_f.

For almost all primes p we have $K_p=Gl_2(\mathbb{Z}_p)$ and the local Hecke algebra $\mathcal{H}(G(\mathbb{Q}_p)//K_p)=\mathbb{Q}[T_p,Z_p,Z_p^{-1}]$ and π_p is simply determined by the eigenvalues ω_p,ω_p of T_p and $T_{p,p}$. on the one dimensional vector space of K_p invariant vectors. Then $\mathbb{Q}(\pi_p)=\mathbb{Q}[\omega_p,\omega_p]$.

Input from the theory of automorphic forms 2

The theory of automorphic forms for Gl_2 provides the following extra informations:

(i) The multiplicity of $H^1(\mathcal{S}^G_{K_f},\mathcal{M}_{\overline{\mathbb{Q}}})(\pi_f)$ is two. (Multiplicity one.)

(ii) If we know the numbers $\omega_p(\pi_f)$, $\omega_p(\pi_f)$ for almost all unramified prime, then π_f is uniquely determined. (Strong multiplicity one.)

(iii) On $H^1(\mathcal{S}^G_{K_f},\mathcal{M}_{\overline{\mathbb{Q}}})(\pi_f)$ we have an action of $\pi_0(G_\infty)$. This group is the quotient of

$$T(\mathbb{R})\cap K_\infty \xrightarrow{\sim} \pi_0(T_\infty) \xrightarrow{\sim} \left\{\begin{pmatrix}\pm1 & 0\\ 0 & \pm1\end{pmatrix}\right\},$$

by the subgroup generated by $\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$.

Under the action of $\pi_0(G_\infty)$ an eigenspace decomposes into two pieces

$$H^1_!(\mathcal{S}^G_{K_f}, \mathcal{M}_{\overline{\mathbb{Q}}})(\pi_f) = \bigoplus_{\varepsilon::\pi_0(G_\infty)\to\{\pm 1\}} H^1_!(\mathcal{S}^G_{K_f}, \mathcal{M}_{\overline{\mathbb{Q}}})(\varepsilon, \pi_f).$$

Both pieces have multiplicity equal to one.

Of course we can find a finite extension $F/\mathbb{Q}$ such that we have this decomposition already over F. If we also invoke the Manin-Drinfeld decomposition, we find

$$H^1_c(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F) = H^1_{\mathrm{Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F) \oplus \bigoplus_{\pi_f,\varepsilon} H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F)(\varepsilon, \pi_f).$$

Now we consider the ring $\mathcal{O}_F \subset F$. For any cohomology group we define the image

$$\mathrm{Im}(H^\bullet_?(?, \tilde{\mathcal{M}}_{\mathcal{O}_F}) \longrightarrow H^\bullet_?(?, \tilde{\mathcal{M}}_F)) =: H^\bullet_?(?, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\mathrm{int}}$$

it is also simply this cohomology divided by the torsion. Then we get a decomposition up to finite quotient isogeny

$$H^1_{\mathrm{Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\mathrm{int}} \oplus H^1_!(\mathcal{S}^G_K, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\mathrm{int}}$$

Then the submodules

$$H^1_{!,\varepsilon}(\mathcal{S}^G_{K_f}, \mathcal{M}_{\mathcal{O}})(\pi_f)_{\mathrm{int}}$$

are the isotypical summands in the cohomology $H^1_!(\mathcal{S}^G_{K_f}, \mathcal{M}_{\mathcal{O}})_{\mathrm{int}}$.

We may also define isotypical quotients. They are obtained if we divide $H^1_!(\mathcal{S}^G_{K_f}, \mathcal{M}_{\mathcal{O}})_{\mathrm{int}}$ by the complementary summand to $H^1_!(\mathcal{S}^G_{K_f}, \mathcal{M}_{\mathcal{O}})_{\mathrm{int}}$, and we denote these quotients by

$$H^1_!(\mathcal{S}^G_{K_f}, \mathcal{M}_{\mathcal{O}})[\varepsilon, \pi_f]_{\mathrm{int}}.$$

We have a natural inclusion

$$H^1_!(\mathcal{S}^G_{K_f}, \mathcal{M}_{\mathcal{O}})(\varepsilon, \pi_f)_{\mathrm{int}} \longrightarrow H^1_!(\mathcal{S}^G_{K_f}, \mathcal{M}_{\mathcal{O}})[\varepsilon, \pi_f]_{\mathrm{int}},$$

and the quotient is a finite module.

The Whittaker model

We assume that π_f is a representation which occurs in the decomposition of $H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_F)$. Let π_∞ be the discrete series representation which has nontrivial cohomology with coefficients in $\mathcal{M}_{\mathbb{C}}$. Now we choose an additive character $\tau : \mathbb{A}_{\mathbb{Q}}/\mathbb{Q} \to S^1$. It may be the best to choose the standard character which is trivial on $\hat{\mathbb{Z}} \subset \mathbb{A}_f$ and at infinity is $x \mapsto e^{2\pi i x}$.

Our representation $\pi_\infty \otimes \pi_f$ (which is known as a module of $\mathbb{C}$-vector spaces) has a unique Whittaker model

$$\mathcal{W}(\pi_\infty \otimes \pi_f, \tau)_{\mathbb{C}}.$$

This is the unique subspace in

$$\mathcal{W}(\tau)_{\mathbb{C}} = \left\{ f : G(\mathbb{A})/K_f \to \mathbb{C} \mid f\left(\begin{pmatrix} 1 & \underline{u} \\ 0 & 1 \end{pmatrix} \underline{g}\right) = \tau(\underline{u}) f(\underline{g}) \right\},$$

which is invariant unter $GL_2(\mathbb{R}) \times \mathcal{H}$ and isomorphic to $\pi_\infty \otimes \pi_f$. The Fourier expansion provides an inclusion

$$\mathcal{W}(\pi_\infty \otimes \pi_f, \tau) \xrightarrow{\mathcal{F}} \mathcal{A}_0(G(\mathbb{Q})\backslash G(\mathbb{A}))$$

$$\mathcal{F}(f)(\underline{g}) = \sum_{t \in \mathbb{Q}^\times} f\left(\begin{pmatrix} t & 0 \\ 0 & 1 \end{pmatrix} \underline{g}\right),$$

where $\mathcal{A}_0$ means the space of cusp forms. This gives us an isomorphism

$$H^1(\mathfrak{g}, K_\infty, \mathcal{W}(\pi_\infty, \tau) \otimes \mathcal{M}_{\mathbb{C}}) \otimes \mathcal{W}(\pi_f, \tau) \xrightarrow{\sim} H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathbb{C}})(\pi_f).$$

We have

$$\begin{aligned} H^1(\mathfrak{g}, K_\infty, \mathcal{W}(\pi_\infty, \tau) \otimes \mathcal{M}_{\mathbb{C}}) &= \mathrm{Hom}_{K_\infty}(\Lambda^1(\mathfrak{g}/\mathfrak{k}), \mathcal{W}(\pi_\infty, \tau) \otimes \tilde{\mathcal{M}}_{\mathbb{C}}) \\ &= \mathbb{C}\,\omega_n + \mathbb{C}\,\omega_{-n} \end{aligned}$$

where I will pin down these two generators later. We assume that $\begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \omega_n = \omega_{-n}$. Then

$$\begin{aligned} \omega_+ &= \tfrac{1}{2}(\omega_n + \omega_{-n}) \\ \omega_- &= \tfrac{1}{2}(\omega_n - \omega_{-n}) \end{aligned}$$

form generators of the spaces

$$\mathrm{Hom}_{K_\infty}(\Lambda^1(\mathfrak{g}/\mathfrak{k}), \mathcal{W}(\pi_\infty, \tau) \otimes \tilde{\mathcal{M}}_{\mathbb{C}})_\pm.$$

Now our general procedure outlined in 2.1.1 provides intertwining operators

$$\mathcal{F}^1_1(\omega_\varepsilon) \; : \; \bigotimes_p \mathcal{W}(\pi_p, \tau) \to H^1(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathbb{C}})_\varepsilon(\varepsilon, \pi_f) \tag{8.41}$$

The integral model for $\mathcal{W}(\pi_p, \tau)$.

Our representation π_p has a field of definition $\mathbb{Q}(\pi_p)$ which is a finite extension of $\mathbb{Q}$. To get this field of definition we look at the space of $\overline{\mathbb{Q}}$-valued functions

$$\mathcal{W}_{\overline{\mathbb{Q}}}(\tau) = \left\{ f : G(\mathbb{Q}_p) \to \overline{\mathbb{Q}} \mid f\left(\begin{pmatrix} 1 & u_p \\ 0 & 1 \end{pmatrix} g_r\right) = \tau(u_p) f(g_p) \right\}.$$

On this space I defined an action of the Galois group ([Ha-Mod]) as follows.

$$f^\sigma(g) = \left(f\left(\begin{pmatrix} t_\sigma^{-1} & 0 \\ 0 & 1 \end{pmatrix} g\right)\right)^\sigma,$$

and $\mathbb{Q}(\pi_p)$ is the number field for which $\mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}(\pi_p))$ is the stabilizer of $\mathcal{W}(\pi_p, \tau)$.

The space $\mathcal{W}_{\overline{\mathbb{Q}}}(\pi_p,\tau)$is finite dimensional over $\overline{\mathbb{Q}}$, and the space of functions which are invariant under $\mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}(\pi_p))$ is a $\mathbb{Q}(\pi_p)$ vector space $\mathcal{W}(\pi_p,\tau)$ on which $\mathcal{H}(G(\mathbb{Q}_p)//K_p)$ acts absolutely irreducible. We have $\mathcal{W}(\pi_p,\tau)\otimes_{\mathbb{Q}(\pi_p)}\overline{\mathbb{Q}} = \mathcal{W}_{\overline{\mathbb{Q}}}(\pi_p,\tau)$.

Of course $\mathbb{Q}(\pi_p)\subset\mathbb{Q}(\pi_f)$, and we define a subring $\mathcal{O}(\pi_f)\subset\mathbb{Q}(\pi_f)$. This is the ring of integers in $\mathbb{Q}(\pi_f)$ but we invert the primes which occur in the conductor of π_f, i.e. all the primes where π_p is ramified. Let us denote the product of these primes by N.

We have the action of $\mathcal{H}^{coh}_{\mathbb{Z}}$ (See 1.2.1.(ii)) on the cohomolgy and hence we get an action of the algebra $\mathcal{H}(G(\mathbb{Q}_p)//K_p)_{\mathbb{Z}}$ on $\mathcal{W}(\pi_p,\tau)$ and this gives us a finitely generated $\mathrm{O}(\pi_p)$- module of endomorphisms. Hence we can find invariant lattices $\mathcal{W}(\pi_p,\tau)_{\mathrm{O}(\pi_p)}$. If we invert a few more primes then we can achieve that two such choices just differ by an element $a\in\mathrm{O}(\pi_p)$. We assume that such a choice of lattices has been made at all primes p. If we are in the unramified case then we will make a very particular choice later. We put $\mathcal{W}_{\mathcal{O}(\pi_f)}(\pi_f,\tau)=\bigotimes_p\mathcal{W}_{\mathcal{O}(\pi_f)}(\pi_p,\tau)$ (See 2.2.7).

If we take an element $\sigma\in\mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ then it conjugates the representation π_p into π_p^σ and we get a map

$$\begin{array}{ccc}\mathcal{W}(\pi_p,\tau) & \xrightarrow{\tilde{\sigma}} & \mathcal{W}(\pi_p^\sigma,\tau)\\ f & \mapsto & f^\sigma\end{array}$$

This map is a semilinear isomorphism.

The periods

Now we have constructed the intertwining operator

$$\mathcal{F}_1^{(1)}(\omega_\varepsilon):\bigotimes_p\mathcal{W}_{\mathcal{O}(\pi_f)}(\pi_p,\tau)\otimes\mathbb{C}\longrightarrow H^1(\mathcal{S}^G,\mathcal{M}_{\mathcal{O}})(\varepsilon,\pi_f)\otimes\mathbb{C},$$

and we can define a complex number $\Omega_\varepsilon(\pi_f)$ such that

$$\Omega_\varepsilon(\pi_f)^{-1}\cdot\mathcal{F}_1^{(1)}(\omega_\varepsilon):\bigotimes_p\mathcal{W}_{\mathcal{O}(\pi_f)}(\pi_f,\tau)\xrightarrow{\sim}H^1(\mathcal{S}^G,\mathcal{M}_{\mathcal{O}})(\varepsilon,\pi_f)\qquad(8.42)$$

provided $\mathcal{O}(\pi_f)$ has class number one. Then this number is called a period and it is unique up to an element in $\mathcal{O}(\pi_f)^\times$. We may also look at the conjugates of $\dots\pi_f^\sigma\dots$ of π_f. We can choose these periods consistently (see [Ha-Mod]) and hence we even get a period vector

$$\Omega_\varepsilon(\Pi_f)^{-1}=(\dots\Omega_\varepsilon(\pi_f^\sigma)^{-1}\dots)_{\sigma:\mathbb{Q}(\pi_f)\to\mathbb{C}}.$$

The modular symbols for Gl_2

We start from $GL_2/\mathbb{Q}$ and a coefficient system $\mathcal{M}_n[r]$. Now we consider the modular symbols arising from the subgroup

$$H=T=\left\{\begin{pmatrix}t_1&0\\0&t_2\end{pmatrix}\right\}$$

Our module $\mathcal{M}_n[r]_{\mathbb{Z}} = \bigoplus_{\nu=0}^{n} \mathbb{Z}X^\nu Y^{n-\nu}$ decomposes into eigenspaces $\mathbb{Z}X^\nu Y^{n-\nu}$. Hence we get

$$H^0(\mathcal{S}^T_{K_f^T}, \tilde{\mathcal{M}}_{\mathcal{O}}) = \bigoplus_{\nu=0}^{n} \bigoplus_{\chi:\mathrm{type}(\chi)=\gamma_\nu} \mathcal{O}c_\chi,$$

and since the Manin-Drinfeld principle is valid we get a canonical decomposition

$$H^1_c(\mathcal{S}^G, \tilde{\mathcal{M}}_{\mathbb{Q}}) = H^1_{\mathrm{Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathbb{Q}}) \oplus H^1_!(\mathcal{S}^G, \tilde{\mathcal{M}}_{\mathbb{Q}}),$$

and this means that we have a canonical section

$$H^1_!(\mathcal{S}^G, \tilde{\mathcal{M}}_{\mathbb{Q}}) \longrightarrow H^1_c(\mathcal{S}^G, \tilde{\mathcal{M}}_{\mathbb{Q}}),$$

and hence we can define the intertwining operator

$$J_{c_{\chi,!}} : H^1_!(\mathcal{S}^G, \tilde{\mathcal{M}}^\vee_F) \longrightarrow \ \mathrm{Ind}_{H(\mathbb{A}_f)}^{G(\mathbb{A}_f)} \ \chi_f^{-1}.$$

Let us assume that we have an isotopical component $H^1_!(\mathcal{S}^G, \tilde{\mathcal{M}}^\vee_{\mathbb{Q}(\pi_f)})(\pi_f)$, then we can consider the composition

$$J_{c_{\chi,!}} \circ \Omega_\varepsilon(\pi_f)^{-1}\mathcal{F}_1^{(1)}(\omega_\varepsilon) : \bigotimes_p \ \mathcal{W}_{\mathcal{O}(\pi_f)}(\pi_p, \tau) \longrightarrow \ \mathrm{Ind}_{\tilde{H}(A_f)}^{\tilde{G}(\mathbb{A}_f)} \ \tilde{\chi}_f^{-1}.$$

The local intertwining operators

We need to investigate the space of intertwining operators

$$\mathrm{Hom}_{G(\mathbb{Q}_p)}(\mathcal{W}(\pi_p, \tau_p) \ , \ \ \mathrm{Ind}_{T(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)} \chi_p^{-1}).$$

Of course we need to assume that the central character $\omega(\pi_p)$ is equal to the character χ_p restricted to the centre. We introduce the subtorus

$$T_1(\mathbb{Q}_p) = \left\{ \begin{pmatrix} t & 0 \\ 0 & 1 \end{pmatrix} \right\}$$

of $T(\mathbb{Q}_p)$ and we restrict χ_p to this subgroup and call this restriction $\chi_p^{(1)}$. For $t \in \mathbb{Q}_p^\times$ we denote by $h(t)$ the matrix $h(t) = \begin{pmatrix} t & 0 \\ 0 & 1 \end{pmatrix}$.

Now it is easy to write down an intertwining operator, namely

$$I_p(f)(g) = \int_{T_1(\mathbb{Q}_p)} f(h(t)g)\chi_p^{(1)}(h(t))d^\times t,$$

where of course $d^\times t$ is an invariant measure on $T_1(\mathbb{Q}_p)$. Of course we have to discuss the convergence of this integral.

Before doing that we convince ourselves that this is the only intertwing operator operator up to a scalar factor, the condition (I_{pp}) is valid. If we apply Frobenius reciprocity we see that

$$\mathrm{Hom}_{G(\mathbb{Q}_p)}(\mathcal{W}(\pi_p, \tau_p) \ , \ \ \mathrm{Ind}_{T(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)} \chi_p^{-1}) = \ \mathrm{Hom}_{T(\mathbb{Q}_p)}(\mathcal{W}(\pi_p, \tau_p) \ , \ \chi_p^{-1})$$

The restriction of the functions in $\mathcal{W}(\pi_p, \tau_p)$ to $T_1(\mathbb{Q}_p)$ is injective (See [Go]) and the image of the restriction map is called the*Kirillov model* $\mathcal{K}(\pi_p, \tau_p)$. On this Kirillov model the torus $T_1(\mathbb{Q}_p)$ acts by translation. It is known that the Kirillov model contains the space $\mathcal{C}_c(\mathbb{Q}_p^\times)$ of Schwartz functions, this are the locally constant functions with compact support on $\mathbb{Q}_p^\times$. This space of Schwartz functions has at most codimension 2 and it is of course invariant under $T_1(\mathbb{Q}_p)$. Hence it is clear that the restriction of our intertwning operator to the space of Schwartz functions is (up to a scalar factor) given by the integral. If our representation is supercuspidal then $\mathcal{K}(\pi_p, \tau_p) = \mathcal{C}_c(\mathbb{Q}_p^\times)$ and we we get existence and uniqueness up to a scalar of the intertwining operator very easily. In the general case we have to show that it extends and for this we have to invoke the theory of local L-functions. If we introduce a parameter $s \in \mathbb{C}$, then the integral

$$\int_{T_1(\mathbb{Q}_p)} f(h(t)g)\chi^{(1)}(h(t)) \cdot |t|^{s-1} d^\times t$$

is convergent for $\Re(s) >> 0$ and can be analytically continued to a meromorphic function in the entire plane with at most two poles (see [J-L], [Go]). In [J-L] the authors attach a local L-function $L(\pi_p \otimes \chi_p^{(1)}, s)$ to $\pi_p \otimes \chi_p^{(1)}$ which has exactly poles for those values of s where the integral does not converge and then

$$I^{loc}(\pi_p, \chi_p^{-1}, s)f(g) = L(\pi_p \otimes \chi_p^{(1)}, s)^{-1} \int_{T_1(\mathbb{Q}_p)} f(h(t)g)\chi^{(1)}(h(t)) \cdot |t|^{s-1} d^\times t$$

provides an intertwining operator

$$I^{loc}(\pi_p, \chi_p^{-1}, s) : \mathcal{W}(\pi_p, \tau_p)_{\mathbb{C}} \to \ \mathrm{Ind}_{T(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)} \chi_p^{-1}| \ \ |^{1-s}$$

which is everywhere holomorphic and non zero. If we evaluate at $s = 1$ we get a generator

$$I^{loc}(\pi_p, \chi_p^{-1}) : \mathcal{W}(\pi_p, \tau_p)_{\mathbb{C}} \to \ \mathrm{Ind}_{T(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)} \chi_p^{-1}.$$

The arithmetic properties of this operator will be discussed in the next section.

In defining the local L-function we have to be a little bit careful, we will give a precise formula further expression for the unramified case further down. Our local L-factor will differ by a shift by $1/2$ in the variable s from the L-factor in [J-L] etc. Will will come back to this point later.

The unramified case

To see what is going on we consider the special case that $\pi_p = \pi_p(\lambda_p)$ is an unramified principal series representation. This means that

$$\lambda_p : \begin{pmatrix} t_1 & * \\ 0 & t_2 \end{pmatrix} \longrightarrow \lambda_{p,1}(t_1) \cdot \lambda_{p,2}(t_2)$$

is an unramified character and $\pi_p(\omega_p)$ is the representation obtained by unitary induction from ω_p, i.e. we consider the space of functions

$$\mathrm{Ind}_{\mathrm{un}}(\lambda_p) = \left\{ f : G(\mathbb{Q}_p) \to \mathbb{C} \mid f\left(\begin{pmatrix} t_1 & * \\ 0 & t_2 \end{pmatrix} g \right) = \lambda_{p,1}(t_1)\lambda_{p,2}(t_2) \cdot |\frac{t_1}{t_2}|_p^{\frac{1}{2}} f(g) \right\},$$

where the functions are locally constant. In this case it is not difficult to compute the intertwining operator to the Whittaker model

$$R_p:\ \mathrm{Ind}_{\mathrm{un}}(\lambda_p)\longrightarrow \mathcal{W}(\pi_p(\lambda_p),\tau_p),$$

it is given by

$$R_p(f)(g)=\int_{U(\mathbb{Q}_p)} f(wug)\overline{\tau_p(u)}du,$$

where $w=\begin{pmatrix}0&-1\\1&0\end{pmatrix}$. Again we have a problem of convergence. To solve this we simply compute the integral. Let us also assume that the additive character τ_p is trivial on

$$\mathbb{Z}_p=U(\mathbb{Z}_p)=\left\{\begin{pmatrix}1&u\\0&1\end{pmatrix}\mid u\in\mathbb{Z}_p\right\},$$

and nontrivial on $\frac{1}{p}\mathbb{Z}_p$. We know that $f(wug)$ becomes constant in the variable u if $u\in p^m\mathbb{Z}$ with m large. Hence we have to compute

$$\sum_{\nu=1}^{\infty}\int_{p^{-\nu+m}\mathbb{Z}_p\setminus p^{-\nu+1+m}\mathbb{Z}_p} f(wug)\overline{\tau_p(u)}du,$$

and for convergence we have to discuss what happens if $\nu\to\infty$. We write $u=p^{-n}\varepsilon$ with $n>>0$ and $\varepsilon\in\mathbb{Z}_p^\times$. Then $wu=wuw^{-1}w$ and

$$wuw^{-1}=\begin{pmatrix}1&0\\-p^{-n}\varepsilon&1\end{pmatrix}=\begin{pmatrix}p^n\varepsilon^{-1}&-1\\0&p^{-n}\varepsilon\end{pmatrix}\begin{pmatrix}0&1\\-1&p^n\varepsilon^{-1}\end{pmatrix}.$$

Then

$$\begin{aligned}f(wug)\quad&=\quad f\left(\begin{pmatrix}p^n\varepsilon^{-1}&-1\\0&p^{-n}\varepsilon\end{pmatrix}\begin{pmatrix}0&1\\-1&p^n\varepsilon^{-1}\end{pmatrix}wg\right)\\ &\qquad \lambda_{p,1}(p)^n\lambda_{p,2}(p)^{-n}p^{-n}f\left(\begin{pmatrix}0&-1\\1&p^n\varepsilon^{-1}\end{pmatrix}wg\right),\end{aligned}$$

and $f\left(\begin{pmatrix}0&-1\\1&p^n\varepsilon^{-1}\end{pmatrix}wg\right)=f(g)$ if $n>>0$, especially it will not depend on ε. This means that for $n>>0$

$$\int_{p^{-n}\mathbb{Z}_p\setminus p^{1-n}\mathbb{Z}_p} f(wug)\overline{\tau(u)}du=\mathrm{const}\int_{p^{-n}\mathbb{Z}_p\setminus p^{+1-n}\mathbb{Z}_p}\overline{\tau(u)}=0,$$

and hence our integral is actually a finite sum.

Let us consider the special case where $f=f_{\lambda_p}\in Iun(\lambda)$ is the spherical function which takes the value 1 at the identity. This means that for $g=b\cdot k$ with $k\in Gl_2(\mathbb{Z}_p)$

$$f_{\lambda_p}\left(\begin{pmatrix}t_1&*\\0&t_2\end{pmatrix}k\right)=\lambda_{p,1}(t_1)\lambda_{p,2}(t_2)\cdot\left|\frac{t_1}{t_2}\right|^{\frac{1}{2}},$$

and we keep our assumption on τ_p. Then our computation yields

$$\begin{aligned} R_p(f_{\lambda_p})(e) &= \int_{U(\mathbb{Q}_p)} f_{\lambda_p}(wu) = \\ & \int_{U(\mathbb{Z}_p)} f_{\lambda_p}(wu)\overline{\tau(u)}du + \sum_{\nu=1}^{\infty} \int_{p^{-\nu}\mathbb{Z}_p \setminus p^{-\nu+1}\mathbb{Z}_p} f_{\lambda_p}(wu)\overline{\tau(u)}du = \\ & 1 + \int_{p^{-1}\mathbb{Z}_p\setminus\mathbb{Z}_p} f_{\lambda_p}(wu)\overline{\tau(u)}du = 1 - \frac{\lambda_{p,1}(p)}{\lambda_{p,2}(p)} p^{-1}, \end{aligned}$$

because all the terms with $\nu \geq 2$ vanish since $\tau_p \mid \frac{1}{p}\mathbb{Z}_p \neq 1$.

The same kind of computation gives us also the value

$$R_p(f_{\lambda_p}) \begin{pmatrix} p^k & 0 \\ 0 & 1 \end{pmatrix}.$$

It is zero for $k < 0$ and for $k \geq 0$ we get

$$p^{-\frac{k}{2}} \left(\lambda_{p,2}(p)^k + \left(1-\frac{1}{p}\right)\lambda_{p,2}(p)^{k-1}\lambda_{p,1}(p)\ldots + \left(1-\frac{1}{p}\right)\lambda_{p,1}(p)^k - \frac{\lambda_{p,1}(p)^{k+1}}{\lambda_{p,2}(p)} p^{-1}\right) =$$

$$p^{-\frac{k}{2}} \left(\lambda_{p,2}(p)^k + \lambda_{p,2}(p)^{k-1}\lambda_{p,1}(p) + \ldots + \lambda_{p,1}(p)^k\right)\left(1 - \frac{\lambda_{p,1}}{\lambda_{p,2}}(p)p^{-1}\right).$$

We put

$$\frac{1}{1-\frac{\lambda_{p,1}}{\lambda_{p,2}}(p)p^{-1}} \quad R_p(f_{\lambda_p}) = \Psi_{\lambda_p}.$$

(If $\frac{\lambda_{p,1}}{\lambda_{p,2}}(p)p^{-1} = 1$ then the induced representation is not irreducible.) This means that Ψ_{λ_p} is the spherical Whittaker function which has value 1 at the identity element.

Now we can discuss the integral Whittaker model at an unramified place p. In this case we assume that $K_p = Gl_2(\mathbb{Z}_p)$ and we put $\mathcal{W}(\pi_p)_{\mathrm{O}(\pi_p)} = \mathrm{O}(\pi_p)\Psi_{\lambda_p}$, the module is of rank one.

We return to our intertwining operator from the Whittaker model to the induced representation $\mathrm{Ind}_{H(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)} \chi_p^{-1}$. We assume that $\chi_p^{(1)}$ is also unramified, we normalize $d^\times t(\mathbb{Z}_p^\times) = 1$. We want to compute the value of the local intertwining operator on Ψ_{λ_p}. Then

$$\begin{aligned} & \int_{\mathbb{Q}_p^\times} \Psi_{\lambda_p}\left(\begin{pmatrix} t & 0 \\ 0 & 1 \end{pmatrix}\right) \chi_p^{(1)}(t)|t|^{s-1}d^\times t = \\ & \sum_{k=0}^{\infty} \Psi_{\lambda_p}\left(\begin{pmatrix} p^k & 0 \\ 0 & 1 \end{pmatrix}\right) \chi_p^{(1)}(p)^k p^{k(1-s)} = \\ & \sum_{k=0}^{\infty} p^{\frac{k}{2}}\left(\lambda_{p,2}(p)^k + \lambda_{p,2}(p)^{k-1}\lambda_{p,1}(p) + \ldots + \lambda_{p,1}(p)^k\right)\chi_p^{(1)}(p)^k p^{-ks} = \\ & \frac{1}{\left(1 - p^{\frac{1}{2}}\lambda_{p,2}(p)\chi_p^{(1)}(p)p^{-s}\right)\left(1 - p^{\frac{1}{2}}\lambda_{p,1}(p)\chi_p^{(1)}(p)p^{-s}\right)} \end{aligned}$$

Now we work with the module $\mathcal{M}_n$, i.e. we do not make a twist by the determinant. If we look at the definition of the Hecke operators on the integral cohomology (See [Heck]) then we notice that in this case we do not need a modification of the operators $T_p, T_{p,p}$ to get them acting on the integral cohomology. We conclude that the numbers

$$p^{1/2}\lambda_{p,1}(p) = \alpha_p, p^{1/2}\lambda_{p,2}(p) = \beta_p$$

are algebraic integers. Since the central character is of type $x \mapsto x^n$ we conclude $\alpha_p\beta_p$ has absolute value p^{n+1} and of course the Weil conjectures imply $|\alpha_p| = |\beta_p| = p^{(n+1)/2}$. The numbers $\alpha_p + \beta_p, \alpha_p\beta_p$ generate the field $\mathbb{Q}(\pi_p)$ and the number $L(\pi \otimes \chi^{(1)}, 1) \in \mathbb{Q}(\pi_p, \chi^{(1)})$. From this we conclude that the local intertwining operator $I^{loc}(\pi_p, \chi_p^{-1})$ is defined over $\mathbb{Q}(\pi_p, \chi^{(1)})$ we get

$$I^{loc}(\pi_p, \chi_p^{-1}) : \mathcal{W}(\pi_p, \tau_p)_{\mathbb{Q}(\pi_p,\chi^{(1)})} \to (\ \mathrm{Ind}_{T(\mathbb{Q}_p)}^{G(\mathbb{Q}_p)} \chi_p^{-1})_{\mathbb{Q}(\pi_p,\chi^{(1)})}$$

In fact it transforms the spherical function Ψ_{λ_p} into the spherical function in the induced module which also takes value one at the identity element.

A similar consideration shows that also at the finitely many remaining places we can define a local intertwining operator $I^{loc}(\pi_p, \chi_p^{-1})$ over $\mathbb{Q}(\pi_p, \chi^{(1)})$. Here we have to look up the table for the local L factors in [Go]. We define the so called local intertwing operator as restricted tensor product

$$I^{loc}(\pi_f, \chi_f^{-1}) = \bigotimes_p I^{loc}(\pi_p, \chi_p^{-1})$$

These local operators are almost compatible with the action of the Galois action. We observe for $\sigma \in \mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ we have the transformation rule $L(\pi_p \otimes \chi_p^{(1)}, 1)^\sigma = L(\pi_p^\sigma \otimes (\chi_p^{(1)})^\sigma, 1)^\sigma$. But the integral is not quite compatible with the action of the Galois group. We have the following commutative diagram: For $\sigma \in \mathrm{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$

$$\begin{array}{cccc} I^{loc}(\pi_f, \chi_f^{-1}): & \mathcal{W}(\pi_f, \tau) & \longrightarrow & \mathrm{Ind}_{H(\mathbb{A}_f)}^{G(\mathbb{A}_f)}\ \chi_f^{-1} \\ & \downarrow\ \sigma & & \downarrow\ \sigma \\ I^{loc}(\pi_f, \chi_f^{-1})\chi_f^{(1)}(\underline{t}_\sigma): & \mathcal{W}(\pi_f^\sigma, \tau) & \longrightarrow & \mathrm{Ind}_{H(\mathbb{A}_f)}^{G(\mathbb{A}_f)}\ (\chi_f^\sigma)^{-1} \end{array}.$$

We discuss the local case where π_p is unramified and $\chi_p^{(1)}$ is ramified and its conductor is $f_p > 0$ Let $T_1(\mathbb{Z}_p)(p^{f_p}) \subset T_1(\mathbb{Z}_p)$ be the subgroup of units $\equiv 1 \mod p^{f_p}$, then character $\chi_p^{(1)}$ is trivial on the on this subgroup but not on $T_1(\mathbb{Z}_p)(p^{f_p-1})$ We normalize $d^\times t_p$ to give $T_1(\mathbb{Z}_p)(p^{f_p})$ the volume one. Again an intertwining operator is given by the integral

$$f \mapsto \int_{T_1(\mathbb{Q}_p)} f(h(t_p)g)\chi^{(1)}(h(t_p)) \cdot d^\times t_p = I_{\chi_p} f(e)$$

We have to optimize our choices (See 8.2.2). For our function f we have to take the spherical Whittaker function Ψ_{λ_p}. For g_p we choose an element

$$g_p = (\begin{pmatrix} 1 & \frac{1}{p^n} \\ 1 & 1 \end{pmatrix}).$$

We want $T_1(\mathbb{Z}_p)(p^{f_p})g_pK_p = g_pK_p$ a simple calculation says that this is the case if and only if

$$\begin{pmatrix} 1 & -\frac{1}{p^n} \\ 1 & 1 \end{pmatrix} h(t_p) \begin{pmatrix} 1 & \frac{1}{p^n} \\ 1 & 1 \end{pmatrix} h(t_p) \in K_p$$

and this says

$$\begin{pmatrix} 1 & (t_p-1)\frac{1}{p^n} \\ 1 & 1 \end{pmatrix} \in K_p.$$

Since $t_p \equiv 1 \mod p^{f_p}$ we see that this is the case if and only if $n \le f_p$. Let us choose such an n, i.e. a g_p.

To compute the intertwining operator we have to evaluate at e (Frobenius reciprocity) and we observe

$$I_{\chi_p}(\Psi_{\lambda_p})(\begin{pmatrix} 1 & \frac{1}{p^n} \\ 1 & 1 \end{pmatrix}) = I_{\chi_p}(\begin{pmatrix} 1 & \frac{1}{p^n} \\ 1 & 1 \end{pmatrix} \Psi_{\lambda_p})(e)$$

By definition this operator is given

$$I_{\chi_p}(\begin{pmatrix} 1 & \frac{1}{p^n} \\ 1 & 1 \end{pmatrix} \Psi_{\lambda_p})(e) = \int_{T_1(\mathbb{Q}_p)} \Psi_{\lambda_p}(\begin{pmatrix} 1 & \frac{t_p}{p^n} \\ 1 & 1 \end{pmatrix} h(t_p))\chi^{(1)}(h(t_p)) \cdot d^\times t_p$$

Since Ψ_{λ_p} is in the Whittaker model the last integral becomes

$$\int_{T_1(\mathbb{Q}_p)} \tau_p(\frac{t_p}{p^n})\Psi_{\lambda_p}(h(t_p))\chi^{(1)}(h(t_p)) \cdot d^\times t_p$$

The value $\Psi_{\lambda_p}(h(t_p))$ depends only on $\mathrm{ord}_p(t_p) = \nu_p$ and hence our integral becomes

$$\sum_{\nu_p=0}^{\infty} \Psi_{\lambda_p}(\begin{pmatrix} p^{\nu_p} & 0 \\ 0 & 1 \end{pmatrix})\chi^{(1)}(p^{\nu_p}) \int_{T^{(1)}(\mathbb{Z}_p)} \tau_p(p^{\nu_p-n}\epsilon)\chi^{(1)}(\epsilon)d^\times\epsilon$$

The integral is a Gauss sum, it vanishes unless $\nu_p - n \le -f_p$, since we have $n \le f_p$ and $\nu_p \ge 0$, the only non zero term is $\nu_p = 0, n = f_p$.

Hence we see that the local contribution at a prime p where π_p is unramified and $\chi^{(1)}$ is ramified is given by the Gauss sum $G(\chi^{(1)},\tau_p)$. Hence we get for a π_f which is globally unramified and a character χ and for the above choice of $\underline{g}_p$ and $\Psi_{\pi_f} = \otimes\Psi_{\lambda_p}$

$$j((x,\underline{g}_f), r_{\lambda,\mu})(\mathcal{F}(\frac{[\omega_\epsilon]}{\Omega(\pi_f,\nu_\epsilon)} \times \Psi_{\pi_f})) = \frac{L(\pi_f\otimes\chi,\mu)}{\Omega(\pi_f,\omega_\epsilon)} \prod_p G(\chi_p^{(1)},\tau_p)c_\chi \quad (8.43)$$

Fixing the period

The actual of computation the period may be a highly non trivial. Actually this may even not be so important. But it is indeed of interest to compute the factorization of the L-values, this means we have to compute the numbers

$$\mathrm{ord}_{\mathfrak{p}}(\frac{L(\pi_f\otimes\chi,\mu)}{\Omega(\pi_f,\omega_\epsilon)}) \quad (8.44)$$

for as many $\mathfrak{p} \subset \mathcal{O}_F$ as possible.

Of course we have problems to fix the period if the class number of $\mathcal{O}_F$ is not one, but this does not matter for the above question, we have to fix a prime p and then we have to choose a good period locally at p. This means we solve the problem alluded to in (8.38) only locally at p.

We discuss this problem in a very special case where our group $G = \mathrm{Gl}_2$, the maximal compact subgroup $K_f = \prod_p \mathrm{Gl}_2(\mathbb{Z}_p)$ and our coefficient system $\mathcal{M}$ is the module of homogenous polynomials $P(X,Y)$ of degree n and coefficients in $\mathbb{Z}$. Hence the Hecke algebra $\mathcal{H}_{K_f} = \otimes'_p \mathcal{H}_{K_p}$ is unramified at all primes p it is commutative. Our isotypical component π_f defines an ideal $\mathcal{I}(\Pi_f) \subset \mathcal{H}_{K_f}$ and the quotient $\mathcal{H}_{K_f}/\mathcal{I}(\Pi_f)$ is an order in the field $\mathbb{Q}(\mathcal{I}(\Pi_f)) = \mathcal{H}_{K_f}/\mathcal{I}(\Pi_f) \otimes \mathbb{Q}$, which is finite extension of $\mathbb{Q}$. (I replaced π_f by Π_f because the ideal does not change if we conjugate π_f the ideal $\mathcal{I}(\Pi_f)$ is associated to the Galois orbit of π_f. I prefer to view $\mathbb{Q}(\Pi_f)$ as an abstract extension of $\mathbb{Q}$.) This ideal $\mathcal{I}(\Pi_f)$ defines a submodule $H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_{\,\mathrm{int}}(\mathcal{I}(\Pi_f)) = \mathrm{Ann}(\mathcal{I}(\Pi_f))$, this is the submodule annihilated by $\mathcal{I}(\Pi_f)$.

We can think of π_f as simply being a modular cusp form f of weight $k = n+2$. To get our isotypical module $H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\,\mathrm{int}}$ we have to find a homomorphism $\sigma : \mathcal{H}_{K_f}/\mathcal{I}(\Pi_f) \to \mathcal{O}_F$ and then

$$H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\,\mathrm{int}}(\pi_f) = H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_{\,\mathrm{int}}(\mathcal{I}(\Pi_f)) \otimes_{\mathcal{H}_{K_f},\sigma} \mathcal{O}_F \tag{8.45}$$

We have the action of complex conjugation, i.e. of $\pi_0(G(\mathbb{R}))$, on the cohomology $H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_{\,\mathrm{int}}(\mathcal{I}(\Pi_f))$ we get the decomposition (up to an isogeny of degree 2^m)

$$H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_{\,\mathrm{int}}(\mathcal{I}(\Pi_f)) \supset H^1_{!,+}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_{\,\mathrm{int}}(\mathcal{I}(\Pi_f)) \oplus H^1_{!,-}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_{\,\mathrm{int}}(\mathcal{I}(\Pi_f)) \tag{8.46}$$

and after taking the tensor product by $\mathbb{Q}$ both summands become one dimensional vector spaces over $\mathbb{Q}(\mathcal{I}(\Pi_f))$. But it is by no means clear that the integral modules are isomorphic.

This becomes a little bit better if tensor by $\mathcal{O}_F$ then then we have again

$$H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\,\mathrm{int}}(\pi_f) \supset H^1_{!(,+}\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\,\mathrm{int}}(\pi_f) \oplus H^1_{!(,-}\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathcal{O}_F})_{\,\mathrm{int}}(\pi_f) \tag{8.47}$$

and now the two summands are are $\mathcal{O}_F$ modules of rank one and get their structure as Hecke-modules from the homomorphism σ. (In a sense $\pi_f = (\Pi_f, \sigma)$) But still they are not necessarily isomorphic. If we want to define the periods we need class number one. But instead of defining a period we define a local periods. If we tensor the semilocal ring $\mathcal{O}_{F,p} = \mathcal{O}_F \otimes \mathbb{Z}_{(p)}$ then the class number problem disappears we can choose a period such that we get an isomorphism

$$\Omega^{(p)}_{\pm}(\pi_f)^{-1} \cdot \mathcal{F}^{(1)}_1(\omega_{\pm}) : \bigotimes_p \mathcal{W}_{\mathcal{O}_{F,p}(\pi_f)}(\pi_f, \tau) \xrightarrow{\sim} H^1_{!,\pm}(\mathcal{S}^G_{K_f}, \mathcal{M}_{\mathcal{O}_{F,p}})(\pi_f) \tag{8.48}$$

Recall that we viewed π_f as a modular form f of weight k we change the notation for the periods slightly and denote them by $\Omega^{(p)}_{\pm}(f)$. Our character χ will now be unramified which implies that it is uniquely determined by its type μ. We put $\nu = \mu + 1$ then we get for $\nu = 1, 2, \dots, k-1$ the following integrality statement

$$\Delta(f)\frac{L(f,\nu)}{\Omega_\pm(f)} \in \mathcal{O}_{F,p} \tag{8.49}$$

But we can still do a little bit better. Recall that we have to evaluate our integral cohomology class on a modular symbol c_μ. This modular symbol is a relative cycle from 0 to $i\infty$ (just along the imaginary axis) loaded by an element $e_\mu = X^\mu Y^{n-\mu}$, we denote it by $[0,i\infty]\times e_\nu$. The index μ runs from zero to n. This is a relative cylce and defines a class in $H_1(\mathcal{S}^G_{K_f},\partial(\mathcal{S}^G_{K_f}),\tilde{\mathcal{M}})$. We have the boundary operator

$$\partial : H_1(\mathcal{S}^G_{K_f},\partial(\mathcal{S}^G_{K_f}),\tilde{\mathcal{M}}) \to H_0(\partial(\mathcal{S}^G_{K_f}),\tilde{\mathcal{M}}). \tag{8.50}$$

We represent the boundary by the circle at $i\infty$ then it is clear that

$$\partial(e_\mu) = e_\mu - we_\mu \tag{8.51}$$

and we see that $\partial(e_\mu)$ is a torsion class if $\mu \neq 0, n$. Not only that it is a torsion class it is annihilated by a power of the Hecke-operator T_p^n. This implies that $T_p^n([0,i\infty]\times e_\mu)$ can be lifted to a homology class in $\tilde{E_\mu} \in H_1(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}})$. But then it is clear that the evaluation of our generator $\xi_\pm$ in $H^1_{!,\pm}(\mathcal{S}^G_{K_f},\mathcal{M}_{\mathcal{O}_{F,p}})(\pi_f)$ on this lifted cycle gives an integral value. Since $\xi_\pm$ is an eigenvalue for the Hecke operator we get for $\mu = 1,..,n-1$ and $\nu = \mu+1$

$$<\xi_\pm,\tilde{E_\mu}> = \pi_f(T_p)^n <\xi,e_\mu> = \pi_f(T_p)^n\frac{L(f,\nu)}{\Omega_{\epsilon(\nu)}(f)} \in \mathcal{O}_{F,p} \tag{8.52}$$

This means that we do not need the factor $\Delta(f)$ in front.

We choose a prime $\mathfrak{p}$ in $\mathcal{O}_F$ lying above p. Let us now assume that $\pi_f(T_p)$ is a unit, i.e. f is ordinary at $\mathfrak{p}$ then we can conclude that

$$\frac{L(f,\nu)}{\Omega^{(p)}_\pm(f)} \in \mathcal{O}_{F,\mathfrak{p}}$$

and consequently

$$\mathrm{ord}_\mathfrak{p}(\frac{L(f,\nu)}{\Omega^{(p)}_\pm(f)}) \geq 0 \text{ for all } 2\leq\nu\leq k-2 \tag{8.53}$$

We also know what we should expect at the argument $\nu = k-1$. In this case $\partial(e_n)$ is not a torsion element, but we know that for all primes ℓ the element $(\ell^{k-1}+1-\pi_f(T_\ell))\partial(e_n)$ is annihilated by a power of T_p. If $b_\mathfrak{p}(f)$ is the minimum of the numbers $\mathrm{ord}_\mathfrak{p}(\ell^{k-1}+1-\pi_f(T_\ell))$ then we can conclude that

$$\mathrm{ord}_\mathfrak{p}(\frac{L(f,\mu)}{\Omega^{(p)}_\pm(f)}) + b_\mathfrak{p}(f) \geq 0 \text{ for } \mu = 1, k-1 \tag{8.54}$$

Hence we can say (still a little bit conjecturally and using Poincare'-duality and the fact that the modular symbols c_μ generate the relative homology. (H. Gebertz, Diploma Thesis Bonn .)

If $\mathfrak{p}$ is ordinary then the numbers $\Omega^{(p)}_\pm(f)$ are the right periods at $\mathfrak{p}$ if and only if one of the non negative numbers in the + or − part of the lists (8.53),(8.54)

$$\mathcal{L}_{f,\mathfrak{p}} = \{\ ord_\mathfrak{p}(\frac{L(f,k-1)}{\Omega^{(p)}_-(f)}) + b_\mathfrak{p}(f),\ ord_\mathfrak{p}(\frac{L(f,k-2)}{\Omega^{(p)}_+(f)}),\dots,\ ord_\mathfrak{p}(\frac{L(f,\nu)}{\Omega^{(p)}_\pm(f)}),\dots\}$$

is zero.

This discussion is interesting in view of the conjectures on congruences in [Ha-Cong]. In this note we make conjectures about some congruences between Siegel and elliptic modular forms, these congruences are congruences modulo a "large" prime and I do not really say what a large prime should be. Already in [Ha-Cong] I address the issue that we have to choose the right period, but there the choice is rather ad hoc.

Now we have a better recipe. The heuristic argument for the existence of the congruences only works if the prime is ordinary for the modular form f. But in this case we have now a much more precise rule to compute the period. For an ordinary prime $\mathfrak{p}$ we should expect a congruence if for one of the members in the above lists we find a strictly positive value. Here we should still be a little bit more careful, my heuristic argument predicts congruences if $\mathfrak{p}$ occurs in the denominator of a ratio

$$\mathrm{ord}_\mathfrak{p}(\frac{\mathcal{L}_{f,\mathfrak{p}}(\nu)}{\mathcal{L}_{f,\mathfrak{p}}(\nu+1)}) < 0\ , \nu = k-2, k-3, \dots, k/2+1$$

so we should pay attention to possible cancellations.

Checking the list of the list of the modular forms of weight 12,16,18,20,22,26 we find that the only cases of ordinary primes for which we expect congruences are indeed the cases $k = 22, \ell = 41$ and $k = 26, \ell = 29, 43, 97$ and they are already in [Ha-Cong]. Here is no cancellation.

It will be very interesting to check the case of the two dimensional space of cusp forms of weight 24. In this case the field $F = \mathbb{Q}(\sqrt{144169})$. Again we find very few instances of ordinary candidates, these are the primes dividing 73, 179 and the congruences have been checked.

But apart from these two cases we have the two divisors of 13, they occur rather frequently in our list $\mathcal{L}_{f,\mathfrak{p}}$ and it seems to be interesting to see what happens.

The modular form f of weight 24 has an expansion with coefficients in $\mathbb{Q}(\omega)$ where $\omega^2 = 144169$, we write the first few terms

$$f(q) = q + 12(45-\omega)q^2 + 36(4715 + 16\cdot\omega)q^3 + 32(395729 - 405\cdot\omega)q^4 + \\ 1410(25911 + 128\cdot\omega)q^5 \cdots + 658(3325311035 - 23131008\cdot\omega)q^{13}\dots \tag{8.55}$$

and this provides the two modular forms $f^{(+)}$ (resp. $f^{(-)}$) with real coefficients which we get if we send ω to the positive root $\sqrt{144169}$ (resp. negative root).

We have the periods $\Omega_\pm(f^{(+)}), \Omega_\pm(f^{(-)})$ and we know that

$$\frac{L(f^{(+)},\nu)}{\Omega_{\epsilon(\nu)}(f^{(+)})}, \frac{L(f^{(-)},\nu)}{\Omega_{\epsilon(\nu)}(f^{(-)})} \in \mathbb{Q}(\sqrt{144169}) \tag{8.56}$$

Looking at the norms of these numbers we find some factors of 13. The prime 13 decomposes in $\mathbb{Z}[\omega]$ and we see that the two prime factors above thirteen are given by the homomorphism $\phi_5 : \omega \mapsto 5 \mod 13.$ and $\phi_8 : \omega \mapsto 8 \mod 13$ We check that $f^{(+)}$ is ordinary at ϕ_8 but not at ϕ_5. But if we look at the prime factor decomposition of $\frac{L(f^{(+)},\nu)}{\Omega_{\epsilon(\nu)}(f^{(+)})}$ then we see that ϕ_5 occurs non trivially but ϕ_8 does not. Hence we do not expect the existence of a Siegel modular form and a congruence modulo ϕ_5 because ϕ_5 is not ordinary for $f^{(+)}$. The prime ϕ_8 is ordinary for $f^{(+)}$ but this prime does not occur in the L-values.

Anton's Congruence

The issue to fix the period becomes even more delicate once we allow ramification. Let us consider the case of the congruence subgroup $\Gamma_0(p)$, this means that our open compact subgroup will be $K_{0,f}(p) = \prod_{q:q\neq p} \mathrm{Gl}_2(\mathbb{Z}_q) \times K_0(p)$. Again we can determine the periods locally at a prime ℓ by evaluating period integrals against certain modular symbols. The point is that we have more modular symbols, because we allow ramification. To get control over these modular symbols we consider the representation $\mathrm{Ind}_{K_{0,f}(p)}^{K_f} \mathbb{1}$, i.e. the induced from the trivial representation of $K_{0,f}(p)$ to the maximal compact subgroup K_f. This representation can be viewed as a representation of $\mathrm{Gl}_2(\mathbb{F}_p)$, it is of dimension $p+1$ and it has the Steinberg-module St_p of dimension p. Then we can consider the cohomology $H^1(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_n \otimes \mathrm{St}_p)$, and new forms f for $\Gamma_0(p)$ correspond to eigenclasses in $H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_n \otimes \mathrm{St}_p)$.

We can construct modular symbols with coefficients in $\tilde{\mathcal{M}}_n \otimes \mathrm{St}_p$. The standard torus $T(\mathbb{F}_p)$ acts on St_p and under this action we get a decomposition into eigenspaces (we invert the divisors of $p(p-1)$ let $R = \mathbb{Z}[\frac{1}{p(p-1)}]$)

$$\mathrm{St}_p \otimes R = \bigoplus_{\chi:\mathbb{F}_p^\times \to \mu_{p-1}} Re_\chi \tag{8.57}$$

(The trivial character occurs two times)

Hence we can define modular symbols $e_\mu \otimes e_\chi$ where e_μ is as above. Then we get integrality for the values

$$\frac{L(f\otimes\chi,\mu)}{\Omega_{\epsilon(\mu,\chi)}(f)} G(\chi,\tau) \tag{8.58}$$

Since we inverted p the Gaussian sum does not play any role. We assume that the modular symbols $e_\mu \otimes e_\chi$ generate the relative homology $H_1(\mathcal{S}^G_{K_f}, \partial(\mathcal{S}^G_{K_f}), \tilde{\mathcal{M}}_n \otimes \mathrm{St}_p \otimes R)$. Hence we can fix the periods locally at a prime ℓ which does not divide $p(p-1)$ and which is ordinary for f. We compute the L-values and then we must have

$$\mathrm{ord}_{\mathfrak{l}}(\frac{L(f\otimes\chi,\mu)}{\Omega_{\epsilon(\mu,\chi)}(f)}) \geq 0 \tag{8.59}$$

and for both signs $\epsilon(\mu,\chi)$ at least one of these numbers has to be zero. Here $\mathfrak{l}$ runs over the divisors of ℓ in $\mathcal{O}_F[\zeta_{p-1}]$.

We want to consider the special case of modular forms of weight 4 for $\Gamma_0(p)$. In this case we have only three critical values $L(f\otimes\chi,\mu)$ for $\mu = 1, 2, 3$.

We are interested in this case because we want to understand the conjectures in [Ha-Cong] also in the case of a non regular coefficient system, especially we want to look at the case of the trivial coefficient system, i.e. the case where the representation is one dimensional. Then we find modular forms of weight four in the boundary cohomology and this forces us to allow ramification. But we want to keep ithe ramification as small as possible.

We start from the group $G = \mathrm{GSp}_2/\mathbb{Z}$, we choose as level subgroup the group $K_f = K^G_{f,p} = \prod_{q:q\neq p} G(\mathbb{Z}_q) \times K_0(p)$, where $K_0(p)$ is the group of $\mathbb{Z}_p$ valued points of the unique non special maximal parahoric subgroup scheme $\mathcal{P}_{\gamma_1}$. (Here γ_1 is the fundamental weight attached to the short root viewed as a cocharacter, we have $<\gamma_1, \alpha_1>= 1, <\gamma_1, \alpha_2>= 0.$). This choice $K^G_{f,p}$ defines an arithmetic subgroup $\Gamma_p \subset \mathrm{GSp}_2(\mathbb{Q})$ which is called the paramodular group.

We consider the homomorphism

$$H^3(\mathcal{S}^G_{K_f}, R) \xrightarrow{r} H^3(\partial(\mathcal{S}^G_{K_f}), R) \tag{8.60}$$

The right hand side contains a contribution coming from the cuspidal cohomology of the stratum of the Siegel parabolic subgroup, this is the contribution $H^1_!(\mathcal{S}^M_{K^M_f}, H^2(\mathfrak{u}_P, R))$. The point is that now that $K^M_f = K_{0,f}(p) = \prod_{q:q\neq p} \mathrm{Gl}_2(\mathbb{Z}_q) \times K_0(p)$, which we introduced above. The M-module $H^2(\mathfrak{u}_P, R)$ is the standard three dimensional representation. Hence this cohomology is described by the space of modular forms of weight 4 for the group $\Gamma_0(p)$.

Any modular (new) form f of weight 4 for $\Gamma_0(p)$, yields a contribution

$$H^1_!(\mathcal{S}^M_{K^M_f}, H^2(\mathfrak{u}_P, R))[f]$$

of rank one over $R \otimes \mathcal{O}_F$. Let us consider the inverse image $H^3(\mathcal{S}^G_{K_f}, R)[f] = r^{-1}(H^1(\mathcal{S}^M_{K^M_f}, H^2(\mathfrak{u}_P, R)[f]))$. We consider the restriction

$$H^3(\mathcal{S}^G_{K_f}, R)[f] \xrightarrow{r_f} H^1(\mathcal{S}^M_{K^M_f}, H^2(\mathfrak{u}_P, R)[f] \tag{8.61}$$

We invoke results from Eisenstein cohomology. Schwermer has shown: This restriction map is surjective if and only if we have $L(f, 2) = 0$ otherwise we encounter a pole of an Eisenstein class.

I also discuss an analogous situation in the appendix of [Ha-Eis]. There I assume that we have no ramification, but I discuss non trivial non regular coefficient systems. A rather speculative computation using the comparison between the Lefschetz and the topological trace formula suggests that in this case

r_f has a non trivial kernel $H^3_!(\mathcal{S}^G_{K_f}, R)[f]$ if and only if the sign of the functional equation for $L(f, s)$ is minus one.

Let us believe that the same is true in this case (and if we do not believe in the trace formula we could also try to explain this kernel as a Gritsenko lift) and we get the exact sequence

$$0 \to H^3_!(\mathcal{S}^G_{K_f}, R)[f] \to H^3(\mathcal{S}^G_{K_f}, R)[f] \xrightarrow{r_f} H^1(\mathcal{S}^M_{K^M_f}, H^2(\mathfrak{u}_P, R)[f], \tag{8.62}$$

where $H^3_!(\mathcal{S}^G_{K_f}, R)[f]$ is the Scholl motive attached to f. This yields an extension class of motives

$$\mathcal{X}(f) \in \mathrm{Ext}^1(R(-2), H^3_!(\mathcal{S}^G_{K_f}, R)[f]). \tag{8.63}$$

Tony Scholl suggests to attach a number to such an extension. More precisely he suggests to construct a suitable biextension, this can be done by the Anderson construction introducing an auxiliary prime p_0.) and then this number should be essentially

$$\frac{\frac{L'(f,2)}{\Omega_+(f)}}{\frac{L(f,3)}{\Omega_-(f)}} \tag{8.64}$$

Under this assumption the denominator $\frac{L(f,3)}{\Omega_-(f)}$ becomes interesting. Since we fixed the period, we can ask whether ordinary primes $\mathfrak{l}$ dividing this number yield denominators of Eisenstein classes and hence congruences. Such a congruence has been detected by Anton Mellit in the case $p = 61$ and $\ell = 43$. Checking the tables of W. Stein we find that for $p = 61$ the cohomology $H^1_!(\mathcal{S}^M_{K^M_f}, H^2(\mathfrak{u}_P, R))$ is of rank 2×15 and decomposes into a 12-dimensional and a 18 dimensional piece (over $\mathbb{Q}$). The 6 dimensional piece corresponds to a modular cusp form f of weight 4 for $\Gamma_0(61)$ its coefficients lie in a field of degree 6 over $\mathbb{Q}$. The sign in the functional equ ation is -1 and we should look for the prime decomposition of the number

$$\frac{L(f,3)}{\Omega_(f)} \tag{8.65}$$

over $\ell = 43$. We know that there is a Siegel modular form for Γ_{61} which is not a Gritsenko lift and satisfies the congruence (Poor-Yuen).The question is whether a divisor $\mathfrak{l}|\ell$ occurs in the value above. But then it becomes clear that we have to obey strict rules to fix the period.

We may also check some other primes p and compute the ratios in (**??**) and look whether they are divisible by interesting primes and whether these primes yield congruences for non Gritsenko lifts.

8.2.4 The L-functions

Again I have to say a few words concerning L-functions.

To get the automorphic L-functions at the unramified places we have to introduce the dual group $G^\vee(\mathbb{C})$ (this is $\mathrm{Gl}_2(\mathbb{C})$ in this case) and a finite dimensional representation r of this group. The definition of the dual group is designed in such a way that the Satake parameter ω_p of an unramified representation at p can be interpreted as a semi simple conjugacy class in $G^\vee(\mathbb{C})$ (see [La]). Therefore we can form the expression

$$L(\pi_p, r, s) = \det(\mathrm{Id} - r(\omega_p)p^{-s})^{-1}$$

and then the global L function $L(\pi, r, s)$ is defined as the product over all these unramified L -factors times a product over suitable L-factors at the finite primes. If we do this for our automorphic forms on Gl_2 and if $r = r_1$ is the tautological representation of $Gl_2(\mathbb{C})$ then we get the local L-factors

$$L(\pi_p, r_1, s) = \frac{1}{(1 - \lambda_{p,2}(p)p^{-s})\,(1 - \lambda_{p,1}(p)p^{-s})}$$

and we see that it differs by a shift by 1/2 from our previous definition. Our earlier L -function was the motivic L-function, its definition does not require the additional datum r. Our automorphic form π defines a motive $\mathbb{M}(\pi)$. This motive has the disadvantage that it does not occur in the cohomology of a variety, it occurs only after we apply a Tate twist to it. The central character $\omega(\pi)$ has type $x \mapsto x^n$ and defines a Tate motive. The automorphic form $\pi \otimes \omega(\pi)^{-1} = \pi^\vee$ occurs in the cohomology

$$H^1(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}[-n]) \supset H^1(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}[-n])(\pi \otimes \omega(\pi)^{-1}) = H^1(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}[-n])(\pi^\vee)$$

where $\mathcal{M}_n[-n]$ is obtained by twisting the original module by the $-n$-th power of the determinant. (See [Ha-Eis], III). This motive occurs in the cohomology of a quasiprojective scheme (See also [Scholl]) Now we adopt the point of view that π_f is a pair (Π_f, ι) (See 1.2.6) and then $\mathbb{M}(\pi)$ defines a system of $\mathfrak{l}$-adic representations $\rho(\pi)_\mathfrak{l}$ which are also labelled by the $\iota : \mathbb{Q}(\pi_f) \to \bar{\mathbb{Q}}$. Then it is Delignes theorem that for unramified primes

$$L(\pi_p, r_1, s - \frac{1}{2}) = L_p((\mathbb{M}(\pi^\vee), s) = \det(\mathrm{Id} - \rho(F_p)_p^{-1} | \mathbb{M}(\pi^\vee)_\mathfrak{l}\, p^{-s})$$

for a suitable choice of $\ell \neq p$.

Weights and Hodge numbers

We may of course look at the motives $\mathbb{M}(\pi)$ which are attached to an eigenspace in $H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}[-k])(\pi)$ in other words we twisted the natural module $\mathcal{M}_n$ by the $-k$-th power of the determinant. Again we get an $\mathfrak{l}$-adic representation $\rho_\mathfrak{l}$ and the Weil conjectures imply that the eigenvalues of the inverse Frobenius $\rho_\mathfrak{l}(F_p^{-1})$ all have the same absolute value $p^{\frac{2k-n+1}{2}}$. The number $2k - n + 1$ is usually called the weight $w(\rho_\mathfrak{l})$ of the Galois representation or also the weight $w(\mathbb{M}(\pi))$ of the motive $\mathbb{M}(\pi)$.

The central character $\omega(\pi)$ of π has a type and if we make the natural identification of G_m with the centre then the type of $\omega(\pi)$ is an integer $\mathrm{type}(\omega(\pi)) \in \mathbb{Z}$ and the formula for the weight is

$$w(\mathbb{M}(\pi)) = -\mathrm{type}(\omega(\pi)) + 1.$$

This weight plays a role if we want to get a first understanding of the analytic properties of the motivic L-functions. Its abcizza of convergence is the line $\Re(s) = w(\mathbb{M}(\pi)) + 1$.

The special case $k = n$ is special, because in this case our motive occurs in the cohomolgy of a variety. The eigenvalues of the Frobenius are algebraic integers and the non zero Hodge numbers are $h^{n+1,0}$ and $h^{0,n+1}$. If k is arbitrary then the centre acts on $\mathcal{M}_n[-k]$ by the character $t(k) = n - 2k$ and the non zero Hodge numbers will be $h^{1+\frac{n-t(k)}{2}, -\frac{n+t(k)}{2}}$. We notice that for an isotypic component $H^1_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}[-k])(\pi)$ the number $t(k)$ is the type of the central character $\omega(\pi)$.

8.2.5 The special values of L-functions

We now observe that the local L factors $L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), s)$ which we introduced in 2.2.6 are actually the local L-factrs of the motivic L-function, i.e.

$$L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), s) = L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), s)$$

Theorem 8.2.2. *With these notations we can give a formula for the composition*

$$J_{c_{\chi,!}} \circ \Omega_\varepsilon(\pi_f)^{-1} \cdot \mathcal{F}_1^{(1)}(\omega_\varepsilon) = \frac{L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), 1)}{\Omega_\varepsilon(\pi_f)} \cdot I^{loc}(\pi_f, \chi_f^{-1})$$

Applications

We evaluate this formula at elements $\psi_f \in \mathcal{W}(\pi_f, \tau)_{\mathrm{O}(\pi_f,\chi)}$ and an element $\underline{g}_f \in G(\mathbb{A}_f)$. We get $\Omega_\varepsilon(\pi_f)^{-1} \cdot \mathcal{F}_1^{(1)}(\omega_\varepsilon)(\psi_f) = \tilde{\psi}_f \in H^1_{!,\varepsilon}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})_{\mathrm{O}(\pi_f,\chi)}$ and

$$J_{c_{\chi,!}}(\psi_f)(\underline{g}_f) = \frac{L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), 1)}{\Omega_\varepsilon(\pi_f)} \cdot I^{loc}(\pi_f, \chi_f^{-1})(\psi_f)(\underline{g}_f))$$

We have seen that $J_{c_{\chi,!}}(\psi_f)(\underline{g}_f)d(\underline{g}_f)$ (Lemma 2.2) is an integer and it is obvious that $d(\underline{g}_f) = \prod_p d(g_p)$. If we choose for ψ_f an element which is also a product $\psi_f(\underline{g}_f) = \prod_p \psi_p(g_p)$ then we get

$$J_{c_{\chi,!}}(\psi_f)(\underline{g}_f) \prod_p d(g_p) = \frac{L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), 1)}{\Omega_\varepsilon(\pi_f)} \cdot \prod_p I_p^{loc}(\pi_p, \chi_p^{-1})(\psi_p)(g_p)d(g_p))$$

The factors in the products over all primes are equal to one at almost all places. Then we have to optimize the choices of ψ_p and g_p. First of all we can choose these data such that all local factors are different from zero. Then we conclude that we have an invariance under Galois for the L-values

$$\left(\frac{L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), 1)}{\Omega_\varepsilon(\pi_f)}\right)^\sigma = \chi^{(1)}(\underline{t}_\sigma) \frac{L(\mathbb{M}((\pi^\vee \otimes (\chi^{(1)})^{-1})^\sigma, 1)}{\Omega_\varepsilon(\pi_f^\sigma)}$$

We may observe that the characters $\chi^{(1)}$ can be written as product of a Dirichlet character and a power of the Tate character, i.e. $\chi^{(1)} = \phi{\cdot}\alpha^{-\nu}$ where $\nu = 0, \dots n$. Now we can write

$$\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}) = \mathbb{M}(\pi^\vee \otimes \phi^{-1}) \otimes \mathbb{Z}(\nu)$$

and

$$L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), 1) = L(\mathbb{M}(\pi^\vee \otimes \phi^{-1}), 1 + \nu)$$

and the arguments $1+\nu$ are exactly the critical arguments for the motive $\mathbb{M}(\pi^\vee \otimes \phi^{-1})$ in the sense of Deligne.

Of course we are now able to prove also some integrality results, it is clear that the left hand side is integral, more precisely it is an element in $\mathrm{O}(\pi_f, \chi_f)$.

Now we have to work with local representations to find out under which conditions we can force the product of local factors to be a unit or at least to bound the primes dividing it. Hence we have a tool to show that

$$\frac{L(\mathbb{M}(\pi^\vee \otimes (\chi^{(1)})^{-1}), 1)}{\Omega_\varepsilon(\pi_f)} \in \mathrm{O}(\pi_f, \chi_f)$$

at least if we invert a few more primes.

The arithmetic interpretation

It is clear that we have some control of the primes that have to be inverted. I call them *small* primes. The main reason why I am interested in the integrality statement for these special values is, that I want to understand what it means if a *large* prime divides these values.

I strongly believe that the large primes dividing these L-values are related to the denominators of Eisenstein classes for the cohomology of the symplectic group, what this means will be explained in 5.6 and we also refer to the notes [kolloquium.pdf]. In the following section I want to give some idea how such a relationship between the arithmetic properties of the L-values and the integral structure of the cohomology as a Hecke-module should look like.

Chapter 9

Eisenstein cohomology

Our starting point is a smooth group scheme $\mathbb{G}/\operatorname{Spec}(\mathbb{Z})$ whose generic fiber $G = \mathbb{G}\times_{\mathbb{Z}}\mathbb{Q}$ is reductive and quasisplit. We assume the group scheme is reductive over the largest possible open subset of $\operatorname{Spec}(\mathbb{Z})$ and at the remaining places it is given by a maximal parahoric group scheme structure. If G is split, then we assume that $\mathbb{G}$ is split. We define $K_f = \mathbb{G}(\hat{\mathbb{Z}}) = \prod_p \mathbb{G}(\mathbb{Z}_p) \subset G(\mathbb{A}_f)$

We choose a Borel subgroup $B/\mathbb{Q}$ and a torus $T/\mathbb{Q} \subset B/\mathbb{Q}$. We assume that $T(\mathbb{A}_f) \cap K_f = T/\hat{\mathbb{Z}})$ is maximal compact in $T(\mathbb{A}_f)$. Let $\lambda \in X^*(T)$ be a highest weight, let $\mathcal{M}_\lambda$ be a highest weight module attached to this weight. It is a $\mathbb{Z}$-module, the module $\mathcal{M}_\lambda \otimes \mathbb{Q}$ is a highest weight module for the group $G/\mathbb{Q}$. We consider

9.1 The Borel-Serre compactification

We consider our space

$$\mathcal{S}^G_{K_f} = G(\mathbb{Q})\backslash G(\mathbb{A})/K_\infty K_f$$

and its Borel-Serre compactification

$$i : \mathcal{S}^G_{K_f} \to \bar{\mathcal{S}}^G_{K_f}.$$

Our highest weight module $\mathcal{M}_\lambda$ provides a sheaf $\tilde{\mathcal{M}}_\lambda$ on these spaces.

We have an isomorphism

$$H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \xrightarrow{\tilde{\sim}} H^\bullet(\mathcal{S}^{\bar{G}}_{K_f}, \tilde{\mathcal{M}}_\lambda)$$

for any coefficient system $\tilde{\mathcal{M}}_\lambda$ coming from a rational representation $\mathcal{M}$ of $G(\mathbb{Q})$. The boundary $\partial\bar{\mathcal{S}}_K$ is a manifold with corners. It is stratified by submanifolds

$$\partial\bar{\mathcal{S}}_K = \bigcup_P \partial_P \mathcal{S}^G_{K_f},$$

where P runs over the $G(\mathbb{Q})$ conjugacy classes of proper parabolic subgroups defined over $\mathbb{Q}$. We identify the set of conjugacy classes of parabolic subgroups with the set of representatives given by the parabolic subgroups that contain our standard Borel subgroup $B/\mathbb{Q}$. Then we have

$$H^\bullet(\partial_P \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) = H^\bullet(P(\mathbb{Q})\backslash G(\mathbb{A})/K_\infty K_f, \tilde{\mathcal{M}}_\lambda)$$

We have a finite coset decomposition

$$G(\mathbb{A}_f) = \bigcup_{\xi_f} P(\mathbb{A}_f)\xi_f K_f,$$

for any $\underline{\xi_f}$ put $K_f^P(\xi_f) = P(\mathbb{A})_f \cap \xi_f K_f \xi_f^{-1}$. Then we have

$$P(\mathbb{Q})\backslash X \times G(\mathbb{A}_f)/K_f = \bigcup_{\xi_f} P(\mathbb{Q})\backslash X \times P(\mathbb{A}_f)/K_f^P(\xi_f)\xi_f,$$

If $R_u(P) \subset P$ is the unipotent radical, then

$$M = P/R_u(P)$$

is a reductive group. For any open compact subgroup $K_f \subset G(\mathbb{A}_f)$(resp. for $K_\infty \subset G_\infty$) we define $K_f^M(\xi_f) \subset M(\mathbb{A}_f)$(resp. $K_\infty^M \subset M_\infty$) to be the image of $K^P(\xi_f)$ in $M(\mathbb{A}_f)$ (resp. M_∞). We put

$$\mathcal{S}^M_{K_f(\xi_f)} = M(\mathbb{Q})\backslash M(\mathbb{A})/K_\infty^M K_f^M(\xi_f)$$

and get a fibration

$$\pi_P : P(\mathbb{Q})\backslash X \times P(\mathbb{A}_f)/K_f^P(\xi_f) \to M(\mathbb{Q})\backslash M(\mathbb{A})/M(\mathbb{Q})\backslash K_\infty^M \times K_f^M(\xi_f)$$

where the fibers are of the form $\Gamma_U\backslash R_u(P)(\mathbb{R})$ and where $\Gamma_U \subset U(\mathbb{Z})$ is of finite index and defined by some congruence condition dictated by $K_f^P(\xi_f)$. The Lie-algebra $\mathfrak{u}$ of $R_u(P)$ is a free $\mathbb{Z}$-module and it is clear that we have an integral version of the van -Est theorem which says:

If $R = \mathbb{Z}[\frac{1}{N}]$ where a suitable set of primes has been inverted then

$$H^\bullet(\Gamma_U\backslash R_u(P)(\mathbb{R}), \tilde{\mathcal{M}}_R) \xrightarrow{\sim} H^\bullet(\mathfrak{u}, \tilde{\mathcal{M}}_R).$$

More precisely we know that the local coefficient system $R^\bullet\pi_{P*}(\tilde{\mathcal{M}})$ is obtained from the rational representation of M on $H^\bullet(\mathfrak{u}, \mathcal{M})$.

Hence we get

$$H^\bullet(\partial_P\mathcal{S}, \tilde{\mathcal{M}}_R) = \bigcup_{\xi_f} H^\bullet(\mathcal{S}^M_{K_f^M(\xi_f)}, \widetilde{H^\bullet(\mathfrak{u}, \mathcal{M})}_R),$$

and

$$H^\bullet(\mathfrak{u}, \mathcal{M}_R) = \bigoplus_{w\in W^P} H^{l(w)}(\mathfrak{u}, \mathcal{M}_R)(w\cdot\lambda),$$

where W^P is the set of Kostant representatives of W/W^M and where $w\cdot\lambda = (\lambda+\rho)^w - \rho$ and ρ is the half sum of positive roots.

The primes which we have to be inverted should be those which are smaller than the coefficients of the dominant weights in the highest weight of $\mathcal{M}$. But at this point we may have to enlarge the set of small primes.

We conclude

The cohomology of the boundary strata $\partial_P \mathcal{S}^G_{K_f}$ with coefficients in $\mathcal{M}$ can be computed in terms of the cohomology of the reductive quotient, where we have coefficients in the cohomology of the Lie algebra of the unipotent radical with coefficients in $\mathcal{M}$

In the following considerations we sometimes suppress the subscripts $K_f, K^M_{K^M_f}$ and so on. Then we mean that the considerations are valid for a fixed level or that we have taken the limit over the K_f. (See the remarks below concerning induction)

9.1.1 The two spectral sequences

The covering of the boundary by the strata $\partial_P\mathcal{S}$ provides a spectral sequence, which converges to te cohomology of the boundary. We can introduce the simplex Δ of types of parabolic subgroups, the vertices correspond to the maximal ones and the full simplex corresponds to the minimal parabolic. To any type of a parabolic P let $d(P)$ its rank, we make the convention that $d(P)-1$ is equal to the dimension of the corresponding face in the simplex. Let $M = M_P = P/R_u(P)$ be the reductive quotient (the Levi quotient). If $Z_M/\mathbb{Q}$ is the connected component of the identity of the center of $M/\mathbb{Q}$ then $d(P)$ is also the dimension of the maximal split subtorus of $Z_M/\mathbb{Q}$ minus the dimension of the maximal split subtorus of $Z_G/\mathbb{Q}$. The covering yields a spectral sequence whose $E_1^{\bullet,\bullet}$ term together with the differentials of our spectral sequence is given by

$$0 \to E_1^{0,q} = \bigoplus_{P,d(P)=1} H^q(\partial_P\mathcal{S},\mathcal{M}) \xrightarrow{d_1^{0,q}} \cdots \to \bigoplus_{P,d(P)=p+1} H^q(\partial_P\mathcal{S},\mathcal{M}) \xrightarrow{d_1^{p,q}} \tag{9.1}$$

where the boundary map $d_1^{p,q}$ is obtained from the restriction maps (See [Gln]). There is also a homological spectral sequence which converges to the cohomology of the boundary. It can be written as a spectral sequence for the cohomology with compact supports. Let d be the dimension of $\mathcal{S}$ then we have a complex

$$\to \bigoplus_{P,d(P)=p+1} H_c^{d-1-p-q-1}(\partial_P\mathcal{S},\mathcal{M}) \xrightarrow{\delta_1} \bigoplus_{P,d(P)=p} H_c^{d-1-p-q}(\partial_P\mathcal{S},\mathcal{M}) \to \tag{9.2}$$

and therefore the $E^1_{\bullet,\bullet}$ term is

$$E^1_{p,q} = \bigoplus_{P,d(P)=p} H_c^{d-1-p-q}(\partial_P\mathcal{S},\mathcal{M})$$

the (higher) differential go from (p,q) to $(p-r, q+1-r)$.

9.1.2 Induction

The description of the cohomology of a boundary stratum is a little bit clumsy, since we are working with the coset decomposition. The reason is that we are working on a fixed level, if we consider cohomology with integral coefficients. If we have rational coefficients then we can pass to the limit. Then

$$H^\bullet(\partial_P \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}) = \lim_{K_f} H^\bullet(P(\mathbb{Q})\backslash G(\mathbb{A})/K_\infty K_f, \tilde{\mathcal{M}}) =$$

$$\mathrm{Ind}_{\pi_0(M(\mathbb{R})\times P(\mathbb{A}_f)}^{\pi_0(G(\mathbb{R})\times G(\mathbb{A}_f)} \lim_{K_f^M} H^\bullet(\mathcal{S}^M_{K_f^M}, \widetilde{H^\bullet(\mathfrak{u},\mathcal{M})}) = \mathrm{Ind}_{\pi_0(M(\mathbb{R}))\times P(\mathbb{A}_f)}^{\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)} H^\bullet(\mathcal{S}^M, \widetilde{H^\bullet(\mathfrak{u},\mathcal{M})}),$$

where the induction is ordinary group theoretic induction. We should keep in our mind that the $\pi_0(M(\mathbb{R}))\times P(\mathbb{A}_f)$ -modules are in fact $\pi_0(M(\mathbb{R}))\times M(\mathbb{A}_f)$-modules. We need some simplification in the notation and we will write for any such $\pi_0(M(\mathbb{R}))\times M(\mathbb{A}_f)$ module H

$$\mathrm{Ind}_{\pi_0(M(\mathbb{R}))\times P(\mathbb{A}_f)}^{\pi_0(G(\mathbb{R}))\times G(\mathbb{A}_f)} H = I_M^G H$$

We will use the same notation for an induction from the torus T to M.

Under certain conditions we also have the notion of induction for Hecke - modules and we can work with integral coefficient systems. This will be discussed at another occasion.

But I want to mention that in the case that K_f is a hyperspecial maximal compact subgroup (in the cases where we are dealing with a split semi-simple group scheme over $\mathrm{Spec}(\mathbb{Z})$ we can take $K_f = \prod \mathbb{G}(\mathbb{Z}_p)$ (see 1.1)) then $G(\mathbb{Q}_p) = P(\mathbb{Z}_p)K_p = B(\mathbb{Z}_p)K_p$ the group theoretic induction followed by taking K_f invariants gives back the original module. In this case we do not have to induce!

Of course we have to understand the coefficient systems $H^\bullet(\mathfrak{u},\mathcal{M})$, for this we need the theorem of Kostant which will be discussed in the next section.

9.1.3 A review of Kostants theorem

At this point we can make the assumption that our group $G/\mathbb{Q}$ is quasisplit, we also assume that $G^{(1)}/\mathbb{Q}$ is simply connected. Then we may assume that $\mathcal{M}_\mathbb{Z}$ is irreducible and of highest weight λ. Let $B/\mathbb{Q}$ be a Borel subgroup, we choose a torus $T/\mathbb{Q} \subset B/\mathbb{Q}$. Let $X^*(T) = \mathrm{Hom}(T\times_\mathbb{Q}\bar{\mathbb{Q}}, \mathbb{G}_m \times_\mathbb{Q} \bar{\mathbb{Q}}$ be the character module, it comes with an action of a finite Galois group $\mathrm{Gal}(F/\mathbb{Q})$, here F is the smallest sub field of $\bar{\mathbb{Q}}$ over which $G/\mathbb{Q}$ splits. Let $T^{(1)}/\mathbb{Q} \subset T/\mathbb{Q}$ the maximal torus in $G^{(1)}/\mathbb{Q}$, then $X^*(T^{(1)})$ contains the set Δ of roots, the subset Δ^+ of positive roots (with respect to B.) The set of simple roots is identified to a finite index set $I = \{1,2,\dots,r\}$, i.e we write the set of simple roots as $\pi = \{\alpha_1,\dots,\alpha_i,\dots,\alpha_r\} \subset \Delta^+$. We assume that the numeration is somehow adapted the Dynkin diagram. The finite Galois group $\mathrm{Gal}(F/\mathbb{Q})$ acts on I and π by permutations. Attached to the simple roots we have the dominant fundamental weights $\{,\dots,\gamma_i,\dots,\gamma_j,\dots\}$ they are related to the simple roots by the rule

$$2\frac{<\gamma_i,\beta_j>}{<\beta_j,\beta_j>}=\delta_{i,j}.$$

The dominant fundamental weights form a basis of $X^*(T^{(1)})$.

Our maximal torus $T/\mathbb{Q}$ is up to isogeny the product of $T^{(1)}$ and the central torus $C/\mathbb{Q}$, i.e. $T=T^{(1)}\cdot C$ and the restriction of characters yields an injection

$$j:X^*(T)\to X^*(T^{(1)})\oplus X^*(C),$$

this becomes an isomorphism if we tensorize by the rationals

$$X^*_{\mathbb{Q}}(T)=X^*(T)\otimes\mathbb{Q}\xrightarrow{\sim}X^*_{\mathbb{Q}}(T^{(1)})\oplus X^*_{\mathbb{Q}}(C).$$

This isomorphism gives us canonical lifts of elements in $X^*(T^{(1)})$ or $X^*(C)$ to elements in $X^*_{\mathbb{Q}}(T)$ which will be denoted by the same letter. Especially the fundamental weights $\gamma_1\dots,\gamma_i,\dots$ are elements in $X^*_{\mathbb{Q}}(T)$.

Let $\lambda\in X^*(T)$ be a dominant weight, our decomposition allows us to write it as

$$\lambda=\sum_{i\in I}a_i\gamma_i+\delta=\lambda^{(1)}+\delta$$

we have $a_i\in\mathbb{Z},a_i\geq 0$ and $\delta\in X^*(C)$. To such a dominant weight λ we have an absolutely irreducible $G\times F$ -module $\mathcal{M}_\lambda$.

We consider maximal parabolic subgroups $P/\mathbb{Q}\supset B/\mathbb{Q}$. These parabolic subgroups are given by the choice of a $\mathrm{Gal}(F/\mathbb{Q})$ orbit $\tilde{i}=J\subset I$ Such an orbit yields a character $\gamma_J=\sum_{i\in J}\gamma_i$ The parabolic subgroup $P/\mathbb{Q}$ provided by this datum is determined by its root system $\Delta^P=\{\beta\in\Delta|<\beta,\gamma_J>\geq 0\}$. The choice of the maximal torus $T\subset P$ also provides a Levi subgroup $M\subset P$ but actually it is better to consider M as the quotient P/U_P.

The set of simple roots of $M^{(1)}$ is the subset $\pi_M=\{\dots,\alpha_i,\dots\}_{i\in I_M}$, where of course $I_M=I\setminus J$. We also consider the group $G^{(1)}\cap M=M_1$. It is a reductive group, it has $T^{(1)}$ as its maximal torus. We apply our previous considerations to this group M_1. It has a non trivial central torus $C_1/\mathbb{Q}$. This torus has a simple description, we pick a root $\alpha_i, i\in J$, we know that J is an orbit under $\mathrm{Gal}(F/\mathbb{Q})$. We have the subfield $F_{\alpha_i}\subset F$ such that $\mathrm{Gal}(F/F_{\alpha_i})$ is the stabilizer of α_i. Then it is clear that

$$C_1\xrightarrow{\sim}R_{F_{\alpha_i}/\mathbb{Q}}(\mathbb{G}_m/F_{\alpha_i}),$$

up to isogeny it is a product of an anisotropic torus $C_1^{(1)}/\mathbb{Q}$ and a copy of $\mathbb{G}_m$. The character module $X^*_{\mathbb{Q}}(C_1)$ is a direct sum

$$X^*_{\mathbb{Q}}(C_1)=X^*_{\mathbb{Q}}(C_1^{(1)})\oplus\mathbb{Q}\gamma_J. \tag{9.3}$$

Here $X^*_{\mathbb{Q}}(C_1^{(1)})=\{\gamma\in X^*_{\mathbb{Q}}(C_1)\mid<\gamma,\sum_{i\in J}\alpha_i>=0\}$. The half sum of positive roots in the unipotent radical is

$$\rho_U=f_P\gamma_J \tag{9.4}$$

where $2f_P>0$ is an integer.

We also have the semi simple part $T^{(1,M)} \subset M^{(1)}$ and again we get the orthogonal decomposition

$$X^*_{\mathbb{Q}}(T^{(1)}) = X^*_{\mathbb{Q}}(T^{(1,M)}) \oplus X^*_{\mathbb{Q}}(C_1) = \bigoplus_{i\in I_M} \mathbb{Q}\alpha_i \oplus \bigoplus_{i\in J} \mathbb{Q}\gamma_i = \bigoplus_{i\in I_M} \mathbb{Q}\gamma_i^M \oplus \bigoplus_{i\in J} \mathbb{Q}\gamma_i.$$

Here we have to observe that the $\gamma_i^M, i \in I_M$ are the dominant fundamental weights for the group $M^{(1)}$, they are the orthogonal projections of the γ_i to the first summand in the above decomposition. We have a relation

$$\gamma_j = \gamma_j^M + \sum_{i\in\tilde{i}} c(j,i)\gamma_i, \text{ for } j \in I_M$$

and we have $c(j,i) \geq 0$ for all $i \in J$.

Let W be absolute Weylgroup and subgroup $W_M \subset W$ the Weyl group of M. For the quotient $W_M\backslash W$ we have a canonical system of representatives

$$W^P = \{w \in W \mid w^{-1}(\pi_M) \subset \Delta^+\}.$$

To any $w \in W$ we define $w\cdot\lambda = w(\lambda+\rho)-\rho$ where ρ us the half sum of positive roots. If we do this with an element $w \in W^P$ then $\mu = w\cdot\lambda$ is a highest weight for $M^{(1)}$ and $w\cdot\lambda$ defines us a module for M. Then Kostants theorem says

$$H^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda) = \bigoplus_{w\in W^P} H^{\ell(w)}(\mathfrak{u}_P, \mathcal{M})(w\cdot\lambda),$$

the summands on the right hand side are the irreducible modules attached to $w\cdot\lambda$, they sit in degree

$$l(w) = \#\{\alpha \in \Delta^+ | w^{-1}\alpha \in \Delta^-\} \tag{9.5}$$

Each isomorphism class occurs only once.

We write

$$\begin{array}{cccc} w\cdot\lambda = & \underbrace{\mu^{(1,M)} + \delta_1} & & +\delta \\ & \in X^*_{\mathbb{Q}}(T^{(1,M)}) \oplus X^*_{\mathbb{Q}}(C_1) & & \oplus X^*(C) \end{array} \tag{9.6}$$

We decompose δ_1 and define the numbers $a(w,\lambda)$ (see (9.3))

$$\delta_1 = \delta_1' + a(w,\lambda)\gamma_J.$$

Then we get

$$w(\lambda+\rho)-\rho = \mu^{(1,M)} + a(w,\lambda)\gamma_J \tag{9.7}$$

We also consider the extended Weyl group $\tilde{W}$, this is the group of automorphisms of the root system. Let $w_0 \in W$ be the element sending all positive roots into negative ones. We have an automorphism $\Theta_- \in \tilde{W}$ inducing $t \mapsto t^{-1}$ on the torus. Let $\Theta = w_0 \circ \Theta_-$. This element induces a permutation on the set π of positive roots, which may be the identity and induces -1 on the determinant. Then

$$\Theta\lambda = \sum_{i\in I} a_{\Theta i}\gamma_i - \delta$$

is a dominant weight and the resulting highest weight module is dual module to $\mathcal{M}_\lambda$. Therefore we get a non degenerate pairing

$$H^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda) \times H^\bullet(\mathfrak{u}_P, \mathcal{M}_{\Theta\lambda}) \to H^{d_{U_P}}(\mathfrak{u}_P, F) = F(-2\rho_U),$$

which respects the decomposition, i.e. we get a bijection $w \mapsto w'$ such that $l(w) + l(w') = d_{U_P}$ and such

$$H^{l(w)}(\mathfrak{u}_P, \mathcal{M}_\lambda)(w \cdot \lambda) \times H^{l(w')}(\mathfrak{u}_P, \mathcal{M}_{\Theta\lambda})(w' \cdot \Theta\lambda) \to H^{d_{U_P}}(\mathfrak{u}_P, F) \qquad (9.8)$$

is non degenerate. We conclude

$$a(w, \lambda) + a(w', \Theta\lambda) = -2f_P. \qquad (9.9)$$

We say that $w \cdot \lambda$ is in the positive chamber if

$$a(w, \lambda) \leq -f_P \qquad (9.10)$$

The element Θ conjugates the parabolic subgroup P into the parabolic subgroup Q, which may be equal to P or not. If $P = Q$ resp. $P \neq Q$ then we say that P is (resp. not) conjugate to its opposite parabolic. If Θ_- is in the Weyl group then all parabolic subgroups are conjugate to their opposite. In this case we have $\Theta = 1$.

Conjugating by the element Θ provides an identification $\theta_{P,Q} : W^P \xrightarrow{\sim} W^{\mathbb{Q}}$. We have two specific Kostant representatives, namely the identity $e \in W^P$ and the element $w_P \in W^P$, this is the element which sends all the roots in U_P to negative roots (the longest element). Its length $l(w_P)$ is equal to the dimension $d_P = \dim(U_P)$.

Any element in $w \in W^P$ can be written as product of reflections

$$w = s_{\alpha_{i_1}} \ldots s_{\alpha_{i_\nu}} \qquad (9.11)$$

where $\nu = l(w)$ and the first factor $\alpha_{i_1} \in J$. We always can complement this product to a product giving the longest element

$$s_{\alpha_{i_1}} \ldots s_{\alpha_{i_\nu}} s_{\alpha_{i_{\nu+1}}} \ldots s_{\alpha_{i_{d_P}}} = w s_{\alpha_{i_{\nu+1}}} \ldots s_{\alpha_{i_{d_P}}} = w_P, \qquad (9.12)$$

The inverse of the element $s_{\alpha_{i_{\nu+1}}} \ldots s_{\alpha_{i_{d_P}}}$ is

$$w' = s_{\alpha_{i_{d_P}}} \ldots s_{\alpha_{i_{\nu+1}}} \in W^Q$$

This defines a second bijection $i_{P,Q} : W^P \xrightarrow{\sim} W^Q$ which is defined by the relation

$$w = w_P \cdot i_{P,Q}(w) = w_P \cdot w', \;\; l(w) + l(w') = d_P \qquad (9.13)$$

The composition $\theta_{P,Q}^{-1} \circ I_{P,Q} : W^P \to W^P$ is the bijection provided by duality.

The element w_P conjugates the Levi subgroup M of P into the Levi subgroup of $Q = w_P P w_P^{-1}$. The element $\tilde{w}_P = \Theta w_P$ conjugates the parabolic subgroup P into its opposite (which is conjugate to Q) and induces an automorphism on the subgroup M which is a common Levi-subgroup of P and its opposite.

If we choose $w = e$ then

$$\sum_{i\in I} a_i\gamma_i + \delta = \sum_{i\in I_M} a_i\gamma_i^M + \sum_{j\in J}(\sum_{i\in I_M} a_i c(i,j) + n_j)\gamma_j + \delta.$$

Since J is the orbit of an element $i \in I$ we see that $< \gamma_j, \alpha_j >$ is independent of j and hence we get easily

$$\sum_{j\in J}(\sum_{i\in I_M} a_i c(i,j) + n_j)\gamma_j = \frac{1}{\#J}(\sum_{j\in J}(\sum_{i\in I_M} a_i c(i,j) + n_j))\gamma_J + \delta'$$

and hence

$$a(e,\lambda) = \frac{1}{\#J}(\sum_{j\in J}(\sum_{i\in I_M} a_i c(i,j) + a_j))$$

If we choose Θ_P then as an M-module $\mathcal{M}_{\Theta_P\cdot\lambda}$ is dual to $\mathcal{M}_{\Theta\lambda}(-2f_J\gamma_J)$. We write $\Theta\lambda + \rho = \sum_{i\in I} a_{\Theta i}\gamma_i - \delta$ and then

$$w_P(\sum_{i\in I} a_i\gamma_i + \delta) = \sum_{i\in I_M} n_{\Theta i}\gamma_i^M - \sum_{j\in J}(\sum_{\Theta i\in I_M} a_{\Theta i}c(\Theta i,\Theta j) + a_{\Theta j})\gamma_j - 2f_J\gamma_J - \delta.$$

and especially we find

$$a(w_P,\lambda) = -(\frac{1}{\#J}(\sum_{j\in J}(\sum_{i\in I_M} a_{\Theta i}c(\Theta i,\Theta j) + a_{\Theta j})) + 2f_J)\gamma_J$$

In general we have the inequalities

$$a(\Theta_P,\lambda) \leq a(w,\lambda) \leq a(e,\lambda).$$

We can write our relation (9.7) slightly differently. We can move the half sum of positive roots to the right and split into $\rho = \rho^M + f_P\gamma_J$. We put $\tilde{\mu}^{(1)} = \mu^{(1,M)} + \rho^M$ and then we write

$$w(\lambda+\rho) = \tilde{\mu}^{(1)} + (a(w,\lambda) + f_P)\gamma_J = \tilde{\mu}^{(1)} + b(w,\lambda)\gamma_J \tag{9.14}$$

and of course now we have

$$b(w,\lambda) + b(w',\Theta\lambda) = 0. \tag{9.15}$$

9.1.4 The inverse problem

Later we will encounter the following problem. Our data are as above and we start from a highest weight for M, we write

$$\mu = \mu^{(1)} + \delta_1 + a\gamma_J + \delta = \sum_{i\in I_M} n_{\Theta i}\gamma_i^M + \delta_1 + a\gamma_J + \delta.$$

We ask whether we can find a λ such that we can solve the equation $(Kost)$. More precisely: We give ourselves only the semi simple component $\mu^{(1)}$ of μ and we ask for the solutions

$$w(\lambda+\rho) = \tilde{\mu}^{(1)} + \dots$$

where $w \in W^P$ and λ dominant, i.e. we only care for the semi simple component.

Let us consider the case where $J = \{i_0\}$, i.e. it is just one simple root. Then the term δ_1 disappears and our equation becomes

$$w(\lambda+\rho) = \tilde{\mu}^{(1)} + b\gamma_{i_0} + \delta,$$

of course the δ is irrelevant, but we want to know the range of the values $b = b(\lambda, w)$ when $\tilde{\mu}^{(1)}$ is fixed, but λ, w vary. Of course it may be empty. Let us fix a w and let us assume we have solved $w(\lambda+\rho) = \tilde{\mu}^{(1)} + \dots$. Then it is clear that the other solutions are of the form $\lambda+\rho+\nu$ where $w\nu \in \mathbb{Q}\gamma_{i_0}$. These ν are of the form $\nu = c\nu_0$ with $c \in \mathbb{Z}$. We write $\nu_0 = \sum_{i\in I} b_i\gamma_i$ and it is easy to see that there must be some $b_i > 0$ and some $b_j < 0$. This implies that $\lambda + c\nu_0$ is dominant if and only if $c \in [M, N]$, an interval with integers as boundary point. This of course implies that -still for a given w - the values $b = b(\lambda, w)$ also have to lie in a fixed finite interval

$$b = b(w, \lambda) \in [b_{\min}(w, \tilde{\mu}^{(1)}), a_{\max}(w, \tilde{\mu}^{(1)})] = I(w, \tilde{\mu}^{(1)}).$$

This will be of importance because these intervals will be related to intervals of critical values of L-functions.

9.2 The goal of Eisenstein cohomology

The goal of the Eisenstein cohomology is to provide an understanding of the restriction map r in theorem (6.2.1). More precisely we assume that we understand (can describe) the cohomology $H^\bullet(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ then we want to understand the image $H^\bullet_{\rm Eis}(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ in terms of this description. Under certain conditions we will construct a section $\mathrm{Eis} : H^i_{\rm Eis}(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,\mathbb{C}}) \to H^i(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda,\mathbb{C}})$. It is clear from the previous considerations that understanding of $H^\bullet(\partial\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ requires understanding cohomology of $H^\bullet(\mathcal{S}^M_{K^M_f}, \widetilde{H^\bullet(\mathfrak{u},\mathcal{M})})$ and we have to compute the differentials in the spectral sequence. These differentials will depend on the Eisenstein cohomology of $H^\bullet(\mathcal{S}^M_{K^M_f}, \widetilde{H^\bullet(\mathfrak{u},\mathcal{M})})$. Under certain conditions the spectral sequence degenerates at E_2 level and I do not know whether this is true in general. In a certain sense it would be much more interesting if this is not the case.

We consider certain submodules in the cohomology of the Borel-Serre compactification for which we can construct a section as above. We start from a maximal parabolic subgroup $P/\mathbb{Q}$, let $M/\mathbb{Q}$ be its reductive quotient. We define

$$H^\bullet_!(\partial_P\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) = \bigoplus_{w\in W^P} H^{\bullet-l(w)}_!(\mathcal{S}^M_{K^M_f}, H^{l(w)}(\mathfrak{u}_P, \tilde{\mathcal{M}})(w\cdot\lambda)) \subset H^\bullet(\partial_P\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \tag{9.16}$$

We will abbreviate $H^{l(w)}(\mathfrak{u}_P, \tilde{\mathcal{M}})(w\cdot\lambda) = \tilde{\mathcal{M}}(w\cdot\lambda)$ where always keep in mind that the element $w \in W^P$ knows what the actual parabolic subgroup is and that $\tilde{\mathcal{M}}(w\cdot\lambda)$ sits in degree $l(w)$.

By definition the inner cohomology is the image of the cohomology with compact supports. This implies that the submodule

$$\bigoplus_{P:d(P)=1} H^q_!(\partial_P \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \subset \bigoplus_{P:d(P)=1} H^q(\partial_P \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) = E_1^{0,q}$$

is annihilated by all differentials $d_\nu^{0,q}$ and hence we get an inclusion

$$i_P : \oplus_{w\in W^P} I_P^G H_!^{\bullet - l(w)}(\mathcal{S}^M_{K_f^M}, \mathcal{M}(w\cdot\lambda)) \to H^\bullet(\partial \mathcal{S}^G_{K_f}, \mathcal{M}_\lambda) \tag{9.17}$$

Taking the direct sum over the maximal parabolic subgroups yields a submodule

$$H_!^\bullet(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \hookrightarrow H^\bullet(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \tag{9.18}$$

The Hecke algebra acts on these two modules. Let us assume that this submodule when tensorized by $\mathbb{Q}$ is isotypical in $H_!^\bullet(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{Q})$. Then we get a decomposition

$$H_!^\bullet(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{Q}) \oplus H^\bullet_{\mathrm{non!}}(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{Q}) = H^\bullet(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{Q}). \tag{9.19}$$

We formulated the goal of the Eisenstein cohomology, we described an isotypical subspace and we know can ask: What is the intersection of $H^\bullet_{\mathrm{Eis}}(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{Q})$ with this subspace, or what amounts to the same, what is $H^\bullet_{!,\,\mathrm{Eis}}(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{Q})$.

The element Θ induces an involution on the set of parabolic subgroups containing B (= set of $G(\mathbb{Q})$ conjugacy classes of parabolic subgroups) two parabolic subgroups $P, Q \supset B$ are called associate if $\Theta P = Q$. We can decompose the cohomology $H_!^\bullet(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{Q})$ into summands attached to the classes of associated parabolic subgroups

$$H_!^\bullet(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{Q}) = \bigoplus_{P:P=\Theta P} H_!^\bullet(\partial_P \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \oplus \bigoplus_{[P,Q]} H_!^\bullet(\partial_P \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \oplus H_!^\bullet(\partial_Q \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \tag{9.20}$$

where in the second sum $Q = \Theta P$. Each summand is a sum over the elements of W^P and then we can decompose under the action of the Hecke algebra. We choose a sufficiently large extension $F/\mathbb{Q}$ and in the case $P = \Theta P$ we get

$$H_!^\bullet(\partial_P \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda \otimes F) = \bigoplus_{w\in W^P} \bigoplus_{\sigma_f} H_!^{\bullet - l(w)}(\mathcal{S}^M_{K_f^M}, \tilde{\mathcal{M}}(w\cdot\lambda)\otimes F)(\sigma_f) \tag{9.21}$$

In the case $P \neq \Theta P = Q$ we group the contributions from the two parabolic subgroups together. To any $w \in W^P$ we have the element $i_{P,Q}(w) = w' \in W^Q$. We also group the terms corresponding to w and w' together. To any σ_f which occurs in $H_!^{\bullet - l(w)}(\mathcal{S}^M_{K_f^M}, H^{l(w)}(\mathfrak{u}_P, \tilde{\mathcal{M}})(w\cdot\lambda)\otimes F)$ we find a $\sigma'_f = \sigma_f^{w_P} |\gamma_{\Theta j}|_f^{2f_Q}$, which occurs in the second summand.

The decomposition into isotypical pieces becomes

$$\bigoplus_{\sigma_f} \big(H_!^{\bullet - l(w)}(\mathcal{S}^M_{K_f^M}, \tilde{\mathcal{M}}(w\cdot\lambda)\otimes F)(\sigma_f) \oplus H_!^{\bullet - l(w')}(\mathcal{S}^{M'}_{K_f^{M'}}, \tilde{\mathcal{M}}(w'\cdot\lambda)\otimes F)(\sigma'_f) \big) \tag{9.22}$$

We can define the second step in the filtration (6.20) as the inverse image of $H_!^\bullet(\partial \mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ under the restriction r.

9.2.1 Induction and the local intertwining operator at finite places

Our modules σ_f are modules for the Hecke algebras $\mathcal{H}^M_{K^M_f} = \otimes_p \mathcal{H}^M_{K^M_p}$. Therefore we can write them as tensor product $\sigma_f = \otimes_p \sigma_p$. We consider a prime p where σ_f is unramified then we get can give a standard model for this isomorphism class. The module H_{σ_p} is the rank one $\mathcal{O}_F$ -module $\mathcal{O}_F$, i.e. it comes with a distinguished generator 1. The Hecke algebra acts by a homomorphism (See 6.3.2)

$$h(\sigma_p) : \mathcal{H}^{(M,w\cdot\lambda)}_{K^M_p,\mathbb{Z}} \to \mathcal{O}_F \tag{9.23}$$

and gives us the Hecke-module structure on H_{σ_p}. We can induce H_{σ_p} to a $\mathcal{H}^G_{K^G_p}$ module. This is actually the same $\mathcal{O}_F$ module but now with an action of the algebra $\mathcal{H}^{(G,\lambda)}_{K^G_p,\mathbb{Z}}$. We simply observe that we have an inclusion $\mathcal{H}^{(G,\lambda)}_{K^G_p,\mathbb{Z}} \hookrightarrow \mathcal{H}^{(M,w'\cdot\lambda)}_{K^M_p,\mathbb{Z}}$ and induction simply means restriction.

It follows easily from the description of the description of the spherical (unramified) Hecke modules via their Satake-parameters that the induced modules H_{σ_p} and $H_{\sigma'_p}$ are isomorphic as $\mathcal{H}^{(G,\lambda)}_{K^G_p,\mathbb{Z}}$ -modules and hence we get that after induction the two summands in (9.22) become isomorphic. We choose a local intertwining operator

$$T_p^{\mathrm{loc}} : H_{\sigma_p} \to H_{\sigma'_p} \tag{9.24}$$

simply the identity.

We postpone the discussion of a local intertwining operator at ramified places.

9.3 The Eisenstein intertwining operator

We start from an irreducible unitary module $H_{\sigma_\infty} \times H_{\sigma_f} = H_\sigma$ and assume that we have an inclusion $\Phi : H_\sigma \hookrightarrow L^2_{\mathrm{cusp}}(M(\mathbb{Q})\backslash M(\mathbb{A}))$. We assume that σ_f occurs in the cohomology $H^\bullet_{\mathrm{cusp}}(\mathcal{S}^M_{K^M_f}, \tilde{\mathcal{M}}(w\cdot\lambda)_\mathbb{C})$ and we assume that $w\cdot\lambda$ is in the positive chamber. We consider Φ as an element of $W(\sigma)$ and for the moment we identify H_σ to its image under Φ. We stick to our assumption that σ occurs with multiplicity one in the cuspidal spectrum.

Then we we can consider the induced module, recall that this is the space of functions

$$\{f : G(\mathbb{A}) \to H_\sigma | f(\underline{pg}) = \bar{\underline{p}} f(\underline{g})\} \tag{Ind}$$

where $\bar{\underline{p}}$ is the image of $\underline{p}$ in $M(\mathbb{A})$. We can define the subspace $H_\sigma^{(\infty)}$ consisting of those f which satisfy some suitable smoothness conditions and then we can define a submodule $\mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma^{(\infty)}$ where the $f(g) \in H_\sigma^{(\infty)}$ and the f themselves also satisfy some smoothness conditions.

We embed this space into the space $\mathcal{A}(P(\mathbb{Q})\backslash G(\mathbb{A}))$ by sending

$$f \mapsto \{g \mapsto f(g)(e_M)\},$$

here $\mathcal{A}$ denotes some space of automorphic forms. This an embedding of $G(\mathbb{A})$-modules or an embedding of Hecke modules if we fix a level.

We have the character $\gamma_P : M \to G_m$, for any complex number z this yields a homomorphism $|\gamma_P|^z : M(\mathbb{A}) \to \mathbb{R}^\times$ which is given by $|\gamma_P| : \underline{m} \mapsto |\gamma_P(\underline{m})|^z$. As usual we denote by $\mathbb{C}(|\gamma_P|^z)$ the one dimensional $\mathbb{C}$ vector space on which $M(\mathbb{A})$ acts by the character $|\gamma_P|^z$. Then we may twist the representation H_σ by this character and put $H_\sigma \otimes |\gamma_P|^z = H \otimes \mathbb{C}(|\gamma_P|^z)$. An element $\underline{g} \in G(\mathbb{A})$ can be written as $\underline{g} = \underline{p}\underline{k}, \underline{p} \in P(\mathbb{A}), \underline{k} \in K_f^0$ where $K_f^0 \supset K_f$ is a suitable maximal compact subgroup and now we define $h(\underline{g}) = |\gamma_P|(\underline{p})$.

Eisenstein summation yields embeddings

$$\mathrm{Eis}: \ \mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma^{(\infty)} \otimes |\gamma_P|^z \to \mathcal{A}(G(\mathbb{Q})\backslash G(\mathbb{A})), \tag{9.25}$$

where

$$\mathrm{Eis}(f)(\underline{g}) = \sum_{\gamma \in P(\mathbb{Q})\backslash G(\mathbb{Q})} f(\gamma \underline{g})(e_M) h(\gamma \underline{g})^z,$$

it is well known that this is locally uniformly convergent provided $\Re(z) >> 0$ and it has meromorphic continuation into the entire z plane (See [Ha-Ch]).

We assumed that H_σ is in the cuspidal spectrum. We get important information concerning these Eisenstein series, if we compute their constant Fourier coefficient with respect to parabolic subgroups: For any parabolic subgroup $P_1/\mathbb{Q} \subset G/\mathbb{Q}$ with unipotent radical $U_1 \subset P_1$ we define (See [Ha-Ch], 4)

$$\mathcal{F}^{P_1}(\ \mathrm{Eis}(f))(\underline{g}) = \int_{U_1(\mathbb{Q})\backslash U_1(\mathbb{A})} \mathrm{Eis}(f)(\underline{u}\underline{g})(e_M) d\underline{u}.$$

This essentially only depends on the $G(\mathbb{Q})$-conjugacy class of $P_1/\mathbb{Q}$. It it also in [Ha-Ch] , 4 that this constant term is zero unless P_1 is maximal and the conjugacy class of P_1 is equal to the conjugacy class of $P/\mathbb{Q}$ or the conjugacy class of $Q/\mathbb{Q}$. (which may or may not be equal to the conjugacy class of $P/\mathbb{Q}$.)

These constant Fourier coefficients have been computed by Langlands, we have to distinguish the two cases:

a) The parabolic subgroup $P/\mathbb{Q}$ is conjugate to an opposite parabolic $Q/\mathbb{Q}$.

In this case we have a Kostant representative $w^P \in W^P$ which conjugates $Q/\mathbb{Q}$ into $P/\mathbb{Q}$ and it induces an automorphism of $M/\mathbb{Q}$. We get a twisted representation $w^P(\sigma)$ of $M(\mathbb{A})$. In the computation of the the constant term we have to exploit that σ is cuspidal and we get two terms:

$$\begin{gathered} \mathcal{F}^P \circ \ \mathrm{Eis}: \ \mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \otimes |\gamma_P|^z \to \\ \mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \otimes |\gamma_P|^z \oplus \ \mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_{w^P(\sigma)} \otimes |\gamma_Q|^{2f_P - z} \subset \mathcal{A}(P(\mathbb{Q})\backslash G(\mathbb{A})). \end{gathered} \tag{9.26}$$

We can describe the image. It is well known, that we can define a holomorphic family

$$T^{\mathrm{loc}}(z): \ \mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \otimes |\gamma_P|^z \to \ \mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_{\sigma^{w^P}} \otimes |\gamma_Q|^{2f_P - z}$$

which is defined in a neighborhood of $z = 0$ and which is nowhere zero. This local intertwining operator is unique up to a nowhere vanishing holomorphic function $h(z)$. It is the tensor product over all places $T^{\mathrm{loc}}(z) = \otimes_v T_v^{\mathrm{loc}}(z)$.

For the unramified finite places the local operator is constant, i.e. does not depend on z and is equal to T_p^{loc} in section (9.2.1) and $T^{\mathrm{loc}}(0) = \otimes_p T_p^{\mathrm{loc}}$. At the remaining factors there is a certain arbitrariness for the choice of the local operator and some fine tuning is appropriate.

We also assume that we have chosen nice model spaces $H_{\sigma_\infty}, H_{\sigma'_\infty}$, and an intertwining operator

$$T_\infty^{\mathrm{loc}} : H_{\sigma_\infty} \to H_{\sigma'_\infty} \tag{9.27}$$

which is normalized by the requirement that it induces the "identity" on a certain fixed K_∞^M type.

Then we get the classical formula of Langlands for the constant term: For $f \in \mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \otimes |\gamma_P|^z$ we get

$$\mathcal{F}^P \circ \mathrm{Eis}(f) = f + C(\sigma, z) T^{\mathrm{loc}}(z)(f), \tag{9.28}$$

where $C(\sigma, \lambda, z)$ is a product of local factors $C(\sigma_v, z)$ and where $C(\sigma_v, z)$ is a function in z which is holomorphic for $\Re(z) \geq 0$ (here we need that $w \cdot \lambda$ is in the positive chamber.) This function compares our local intertwining operator to an intertwining operator which is defined by the integral.

The computation of this factor is carried out in H. Kims paper in [C-K-M], chap. 6. He expresses the factor in terms of the automorphic L function attached to σ_f. To formulate the result of this computation we have to recall the notion of the dual group (7.0.6). Inside the dual group ${}^LG$ we have the dual group ${}^LM$ which acts by conjugation on the Lie algebra $\mathfrak{u}_P^\vee$. The set of roots $\Delta^+_{U_P^\vee}$ is a set of cocharacters of $T/\mathbb{Q}$, a coroot $\alpha^\vee \in \Delta^+_{U_P}$ defines a one-dimensional root subgroup $\mathfrak{u}^\vee_{P,\alpha^\vee}$. The ${}^LM$ -module $\mathfrak{u}_P^\vee$ decomposes into submodules. We recall that the maximal parabolic subgroup $P/\mathbb{Q}$ was obtained from the choice of a Galois-orbit $\tilde{i} \subset I$ (9.1.3) and any

$$\alpha^\vee \in \Delta^+_{U_P^\vee},\ \chi = a(\alpha^\vee, \tilde{i})\chi_{\tilde{i}} + \sum_{j \notin \tilde{i}} m_{\tilde{i},j}\chi_j. \tag{9.29}$$

Here the coefficients are integers ≥ 0 and $a(\alpha^\vee, \tilde{i}) > 0$. For a given integer $a > 0$ we define

$$\mathfrak{u}_P^\vee[a] = \bigoplus_{\alpha^\vee : a(\alpha^\vee, \tilde{i}) = a} \mathfrak{u}^\vee_{P,\alpha^\vee} \tag{9.30}$$

it is rather obvious that $\mathfrak{u}_P^\vee[a]$ is an invariant submodule under the action of M and actually it is even irreducible. Let us denote the representation of $M/\mathbb{Q}$ on $\mathfrak{u}_P^\vee[a]$ by $r_a^{\mathfrak{u}_P^\vee}$. In the following η_a will be the highest weight of $r_a^{\mathfrak{u}_P^\vee}$.

With these notations we get the following formula for the local factor at p (See[Kim])

$$C_p(\sigma, z) = \prod_{a=1}^{r} \frac{L^{\mathrm{aut}}(\sigma_p, r_a^{\mathfrak{u}_P^\vee}, a(z - f_P))}{L^{\mathrm{aut}}(\sigma_p, r_a^{\mathfrak{u}_P^\vee}, a(z - f_P) + 1)} T_p^{\mathrm{loc}}(z)(f) \tag{9.31}$$

We do not discuss the ramified finite places, from now on we assume that σ_f is unramified. Then we get

$$C(\sigma, z) = C(\sigma_\infty, z) \prod_p C_p(\sigma_p, z) = C(\sigma_\infty, z) \prod_{a=1}^{r} \frac{L^{\text{aut}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, a(z - f_P))}{L^{\text{aut}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, a(z - f_P) + 1)}$$

The local factor at infinity depends on the choice of T_∞^{loc}, in 1.2.4 we gave some rules how to fix it, if it is not zero on cohomology.

b) The opposite group $Q/\mathbb{Q}$ is not conjugate to $P/\mathbb{Q}$, then we have to compute two Fourier coefficients namely $\mathcal{F}^P$ and $\mathcal{F}^Q$ in this case we get

$$\mathcal{F}: \ \text{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \otimes |\gamma_P|^z \xrightarrow{\mathcal{F}^P \oplus \mathcal{F}^Q}$$

$$\text{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \otimes |\gamma_P|^z \oplus \ \text{Ind}_{Q(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \otimes |\gamma_Q|^{2f_P - z} \subset \mathcal{A}(P(\mathbb{Q})\backslash G(\mathbb{A})) \oplus \mathcal{A}(Q(\mathbb{Q})\backslash G(\mathbb{A})).$$

and again we get

$$\mathcal{F} \circ \ \text{Eis}(f) = f + C(\sigma_\infty, z) \prod_a \frac{L^{\text{aut}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, a(z - f_P))}{L^{\text{aut}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, a(z - f_P) + 1)} T^{\text{loc}}(z)(f), \quad (9.32)$$

where now $T^{\text{loc}}(z)$ is a product of local intertwining operators

$$T_v^{\text{loc}}: \ \text{Ind}_{P(\mathbb{Q}_v)}^{G(\mathbb{Q}_v)} H_{\sigma_v} \otimes |\gamma_P|^z \to \ \text{Ind}_{Q(\mathbb{Q}_v)}^{G(\mathbb{Q}_v)} H_{\sigma_v^{w_P}} \otimes (2f_P - z).$$

It is also due to Langlands that the Eisenstein intertwining operator is holomorphic at $z = 0$ if the factor in front of the second term is holomorphic at $z = 0$. Up to here σ can be any representation occurring in the cuspidal spectrum of M.

Now we assume that we have a coefficient system $\mathcal{M} = \mathcal{M}_\lambda$ and a $w \in W^P$ such that our σ_f occurs in $H_!^{\bullet - l(w)}(\mathcal{S}_{K_f^M}^M, \tilde{\mathcal{M}}(w \cdot \lambda) \otimes F)$. Then we find a $(\mathfrak{m}, K_\infty^M)-$ module H_{σ_∞} such that $H^\bullet(\mathfrak{m}, K_\infty^M, H_{\sigma_\infty} \otimes \mathcal{M}(w \cdot \lambda)) \neq 0$. We also find an embedding

$$\Phi_\iota : H_{\sigma_\infty} \otimes H_{\sigma_f} \otimes_{F,\iota} \mathbb{C} \hookrightarrow L^2_{\text{cusp}}(M(\mathbb{Q})\backslash M(\mathbb{A})) \quad (9.33)$$

Let us assume that $w \cdot \lambda$ or equivalently σ_f are in the positive chamber. In case a) we have holomorphicity at $z = 0$ if the weight λ is regular (See [Schw]) and in case b) the Eisenstein series is always holomorphic at $z = 0$. In this section that we assume that the Eisenstein series is holomorphic at $z = 0$ and hence we can evaluate at $z = 0$ in (9.179) and get an intertwining operator

$$\text{Eis} \circ \Phi_\iota : \ \text{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \to \mathcal{A}(G(\mathbb{Q})\backslash G(\mathbb{A})). \quad (9.34)$$

We get a homomorphism on the de-Rham complexes

$$\text{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \ \text{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} H_\sigma \otimes_{F,\iota} \mathbb{C} \otimes \mathcal{M}_\lambda) \to \ \text{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{A}(G(\mathbb{Q})\backslash G(\mathbb{A})) \otimes \tilde{\mathcal{M}}_\lambda) \quad (9.35)$$

We introduce the abbreviation $H_{\iota\circ\sigma_f} = H_{\sigma_f} \otimes_{F,\iota} \mathbb{C}$ and decompose $H_{\iota\circ\sigma} = H_{\sigma_\infty} \otimes H_{\iota\circ\sigma_f}$. We compose (9.35) with the constant term and get

$$\mathcal{F} \circ \mathrm{Eis}^\bullet : \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} H_{\sigma_\infty} \otimes \mathcal{M}_\lambda) \otimes H_{\iota\circ\sigma_f} \to$$
$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} H_{\sigma_\infty} \otimes \mathcal{M}_\lambda) \otimes H_{\iota\circ\sigma_f}) \oplus\ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{Q(\mathbb{R})}^{G(\mathbb{R})} H_{\sigma'_\infty} \otimes \mathcal{M}_\lambda) \otimes H_{\iota\circ\sigma'_f}) \tag{9.36}$$

where $P = Q$ in case a).

We choose an $\omega \in\ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} \otimes \mathcal{M}_\lambda)$ and consider classes $\omega\otimes\psi_f$ and map them by the Eisenstein intertwining operator to the cohomology (or the de-Rham complex) on $\mathcal{S}^G_{K_f}$. Then the restriction of of the Eisenstein cohomology to the boundary is given by the classes

$$\Phi_\iota(\omega \otimes \psi_f + \frac{1}{\Omega(\sigma_f)} C(\sigma_\infty, \lambda) C(\sigma_f, \lambda) T^{\mathrm{loc}}_\infty(\omega) \otimes T^{\mathrm{loc}}_f(\psi_f)) \tag{9.37}$$

Here the factor $C(\sigma_f, \lambda)$ can be expressed in terms of the cohomological L-function. Translating the formula (9.31) yields (see 9.14)

$$C(\sigma_f, \lambda) = \prod_a \frac{L^{\mathrm{coh}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, < \eta_a, \tilde{\mu}^{(1)} > -b(w,\lambda) < \eta_a, \gamma_P >)}{L^{\mathrm{coh}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, < \eta_a, \tilde{\mu}^{(1)} > -b(w,\lambda) < \eta_a, \gamma_P > +1)} \tag{9.38}$$

We may complete the cohomological L-function by the correct factor at infinity and replace the ratio of L-values by the corresponding ratio of values for the completed $L-$ function. By definition we have $< \eta_a, \gamma_P >= a$ and then our formula for the second term in (9.37) becomes

$$\frac{1}{\Omega(\sigma_f)} \prod_a \frac{\Lambda^{\mathrm{coh}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, < \eta_a, \tilde{\mu}^{(1)} > -ab(w,\lambda))}{\Lambda^{\mathrm{coh}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, < \eta_a, \tilde{\mu}^{(1)} > -ab(w,\lambda) + 1)} C^*(\sigma_\infty, \lambda) T^{\mathrm{loc}}_\infty(\omega) \otimes T^{\mathrm{loc}}_f(\psi_f)) \tag{9.39}$$

This formula needs some comments. The factor $C^*(\sigma_\infty) T^{\mathrm{loc}}_\infty$ is a representation theoretic contribution it is not easy to understand. Experience shows that becomes very simple at the end. In SecOps.pdf we discuss the special case of the symplectic group.

The number $\Omega(\sigma_f)$ is a period, it will be discussed later.

We see that the constant term is the sum of two terms. The first term reproduces the original class from which we started. We assumed that w or $w \cdot \lambda$ it is in the positive chamber (see(9.10)). The second term is some kind of scattering term which is the image of the first term under an intertwining operator. In case a) the restriction of the second term gives a class in the same stratum, in case b) the restriction of the second term gives a class in a second stratum.

At this point I formulate a general principle

Under certain circumstances the second term is of fundamental arithmetic interest, it contains relevant arithmetic information.

To exploit this information we have to understand several aspects of the behavior of this second term in the constant term. We have to recall that is obtained as the evaluation of a meromorphic function $C(\sigma_f, \lambda, z)$ at $z = 0$, i.e. we have to know whether it has pole at $z = 0$ or not. We also have to understand the contribution $C(\sigma_\infty, \lambda) T_\infty^{\text{loc}}$, and we have to understand the arithmetic nature of this term, it is a product and some of the factors yield an algebraic number and the rest will have a motivic interpretation. This is explained further down and in [Mix-Mot-2013.pdf].

We give some more detailed indications how such arithmetic applications may look like. We assume that $w \cdot \lambda$ is in the positive chamber and $l(w) \geq l(w')$. Let us also assume that the Eisenstein intertwining operator is holomorphic at $z = 0$. Then we have to look at

$$T_\infty^{\text{loc},\bullet} : \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} H_{\sigma_\infty} \otimes \mathcal{M}_\lambda) \to \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} H_{\sigma'_\infty} \otimes \mathcal{M}_\lambda) \tag{9.40}$$

The two complexes can be described by the Delorme isomorphism

$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} H_{\sigma_\infty} \otimes \mathcal{M}_\lambda) \xrightarrow{\sim} \bigoplus_{w \in W^P} \mathrm{Hom}_{K_\infty^M}(\Lambda^{\bullet - l(w)}(\mathfrak{m}_\mathbb{C}^{(1)}/\mathfrak{k}^M)), H_{\sigma_\infty} \otimes \mathcal{M}(w \cdot \lambda)) \tag{9.41}$$

Our intertwining operator respects this decomposition and we get

$$T_\infty^{\text{loc},\bullet}(w) : \ \mathrm{Hom}_{K_\infty^M}(\Lambda^{\bullet - l(w)}(\mathfrak{m}_\mathbb{C}^{(1)}/\mathfrak{k}^M)), H_{\sigma_\infty} \otimes \mathcal{M}(w \cdot \lambda)) \to$$
$$\mathrm{Hom}_{K_\infty^M}(\Lambda^{\bullet - l(w')}(\mathfrak{m}_\mathbb{C}^{(1)}/\mathfrak{k}^M)), H_{\sigma'_\infty} \otimes \mathcal{M}(w' \cdot \lambda))$$

Now we know that for regular representations $\mathcal{M}_\lambda$ the cohomology $H^\nu(\mathfrak{m}, K_\infty^M, H_{\sigma_\infty} \otimes \mathcal{M}(w \cdot \lambda))$ is non zero only for ν in a very narrow interval around the middle degree (See [Vo-Zu], Thm. 5.5). If the difference $|l(w) - l(w')|$ is greater than the length of this interval, then the following condition is fulfilled

In any degree $T_\infty^{\text{loc},\bullet}(w)$ induces zero on the cohomology. (Tzero)

In this cases (and under the assumption that the Eisenstein series is holomorphic at $z = 0$) the Eisenstein intertwining operator gives us a section for the Hecke-modules

$$\mathrm{Eis}_\mathbb{C} : H^{q - l(w)})(\mathcal{S}_{K_f^M}^M, \mathcal{M}(w \cdot \lambda) \otimes \mathbb{C})(\sigma_f) \to H^q(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C}) \tag{9.42}$$

9.4 The special case Gl_n

Our group is Gl_n/Q and we choose a parabolic subgroup P containing the standard Borel subgroup and with reductive quotient $M = \mathrm{Gl}_{n_1} \times \mathrm{Gl}_{n_2} \times \cdots \times \mathrm{Gl}_{n_r}$. We want to construct Eisenstein cohomology classes in $H^\bullet(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_{\lambda,\mathbb{C}})$

starting from cuspidal classes in $H^\bullet(\partial_P\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\lambda,\mathbb{C}})$. For an element $w\in W^P$ we write

$$w(\lambda+\rho)=\underline{\mu}^{(1)}-b_1(w,\lambda)\gamma_{n_1}-b_2(w,\lambda)\gamma_{n_1+n_2}+\dots-b_r(w,\lambda)\gamma_{n_1+\dots+n_{r-1}}+d\delta. \tag{9.43}$$

It is the sum of the semi simple part (with respect to M)

$$\underline{\mu}^{(1)}=(b_1\gamma^M_1+\dots+b_{n_1-1}\gamma^M_{n_1-1})+(b_{n_1+1}\gamma^M_{n_1+1}+\dots b_{n_1+n_2-1}\gamma^M_{n_1+n_2-1})+\dots \tag{9.44}$$

$$=\mu^{(1)}_1+\dots+\mu^{(1)}_r \tag{9.45}$$

and the abelian part $\underline{\mu}^{\mathrm{ab}}$.

We assume that $b_i(w,\lambda)\geq 0$ i.e. $w(\lambda+\rho)$ is in the negative chamber and we also assume that the $\mu^{(1)}_i$ are self dual, this is a condition on λ,w. We decompose the strongly inner cohomology

$$H^\bullet_{\mathrm{cusp}}(\partial_P\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_\lambda)=\bigoplus_{w\in W^P}\bigoplus_{\underline{\sigma}_f}\mathrm{Ind}^G_P H^{\bullet-l(w)}_{\mathrm{cusp}}(\mathcal{S}^M_{K^M_f},\tilde{\mathcal{M}}_{w\cdot\lambda})(\underline{\sigma}_f) \tag{9.46}$$

The Künneth-theorem implies that $\underline{\sigma}_f=\sigma_{1,f}\otimes\sigma_{2,f}\otimes\dots\otimes\sigma_{r,f}$. At an unramified place p then this module has a Satake parameter

$$\omega_p(\sigma_f)=\{\omega_{1,p},\dots,\omega_{n_1,p},\omega_{n_1+1,p},\dots,\omega_{n_1+n_2,p},\dots\}$$

where the first n_1 entries are the Satake parameters of $\sigma_{1,f}$ and so on.

We choose an $\iota:E\to\mathbb{C}$. We take an irreducible submodule $H_{\underline{\sigma}_f}$ then we find an irreducible $(\mathfrak{g},K^M_\infty)$-module $H_{\underline{\sigma}_\infty}$ and an embedding

$$\Phi: H_{\underline{\sigma}_\infty}\otimes H_{\underline{\sigma}_f}\otimes_{E,\iota}\mathbb{C}=H_{\underline{\sigma}}\hookrightarrow\mathcal{C}_{\mathrm{cusp}}(M(\mathbb{Q})\backslash M(\mathbb{A})) \tag{9.47}$$

For $\underline{z}=(z_1,z_2,\dots,z_{r-1}),z_i\in\mathbb{C}$ we define the character

$$|\gamma_P|^{\underline{z}}=|\gamma_{n_1}|^{z_1}|\gamma_{n_1+n_2}|^{z_2}\dots|\gamma_{n_1+n_2+\dots+n_{r-1}}|^{z_{r-1}}:M(\mathbb{A})\to\mathbb{C}^\times$$

By the usual summation process we get an Eisenstein intertwining operator

$$\mathrm{Eis}(\underline{\sigma},\underline{z}):I^G_PH_{\underline{\sigma}}\otimes|\gamma_P|^{\underline{z}}\to\mathcal{A}(G(\mathbb{Q})\backslash G(\mathbb{A})) \tag{9.48}$$

the series is locally uniformly converging in a region where all $\Re(z_i)>>0$ and hence the Eisenstein intertwining operator is holomorphic in this region. We know that it admits a meromorphic extension into the entire $\mathbb{C}^{r-1}$.

We want to evaluate at $\underline{z}=0$ this is possible if $\mathrm{Eis}(\underline{\sigma},\underline{z})$ is holomorphic at $\underline{z}=0$, we have to find out what happens at $\underline{z}=$ we have to consider the constant term (constant Fourier coefficient) of $\mathrm{Eis}(\underline{\sigma},\underline{z})$ along parabolic subgroups P_1. (See [H-C]) These constant Fourier coefficients a given by integrals

$$\mathcal{F}^{P_1}:f(\underline{g})\mapsto\int_{U_{P_1}(\mathbb{Q})\backslash U_{P_1}(\mathbb{A})}f(\underline{u}\underline{g})d\underline{u}. \tag{9.49}$$

It suffices to compute these constant terms only for parabolic subgroups containing our given maximal torus. It is shown in [H-C] that the constant term evaluated at $\mathrm{Eis}(\underline{\sigma},\underline{z})(f)$ is zero unless P and P_1 are associate, this means that the Levi subgroups M and M_1 are isomorphic. (For this we need the cuspidality condition (See [H-C],)(But then we can find an element in the Weyl group which conjugates M into M_1 and hence we may assume that P and P_1 both contain our given Levi subgroup M. Of course now P_1 may not contain the standard Borel subgroup.)

We may also assume that $n_1 = n_2 = \cdots = n_{j_1} < n_{j_1+1} = \cdots = n_{j_1+j_2} < \cdots < n_{j_1+\dots j_{s-1}+1} = \cdots = n_{j_1+\dots+j_s} = n_r$, Then it is easy to see that the number of conjugacy classes of parabolic subgroups which contain M is equal to $r!/j_1!j_2!\dots j_s!$.

We compute $\mathcal{F}^{P_1}\circ\ \mathrm{Eis}(\underline{\sigma},\underline{z})(f)$ following [H-C], . By definition (adelic variables in $U(\mathbb{A}), P(\mathbb{A}),\dots$are underlined)

$$\mathcal{F}^{P_1}\circ\ \mathrm{Eis}(\underline{\sigma},\underline{z})(f)(\underline{g}) = \int_{U_{P_1}(\mathbb{Q})\backslash U_{P_1}(\mathbb{A})} \sum_{a\in P(\mathbb{Q})\backslash G(Q)} f_{\underline{z}}(a\underline{u}\underline{g})d\underline{u} \tag{9.50}$$

Let W_M be the Weyl group of M, the Bruhat decomposition yields $G(\mathbb{Q}) = \bigcup_{w\in W} P(\mathbb{Q})\backslash wP_1(\mathbb{Q})$, put $P_1^{(w)}(\mathbb{Q}) = w^{-1}P(\mathbb{Q})w\cap P_1(\mathbb{Q})$ then our expression becomes (we pull the summation over W to the front)

$$\mathcal{F}^{P_1}\circ\ \mathrm{Eis}(\underline{\sigma},\underline{z})(f)(\underline{g}) = \sum_{W_{M_1}\backslash W^{M,M_1}/W_M} \int_{U_{P_1}(\mathbb{Q})\backslash U_{P_1}(\mathbb{A})} \sum_{b\in P_1^{(w)}(\mathbb{Q})\backslash P_1(\mathbb{Q})} f_{\underline{z}}(wb\underline{u}\underline{g})d\underline{u} \tag{9.51}$$

where W_M is the Weyl group of M. If now for a given w the intersection of algebraic groups $w^{-1}U_1w\cap M = V$ has dimension >0, then this intersection is the unipotent radical of a proper parabolic subgroup of M. Since σ is cuspidal the integral over $V(\mathbb{Q})\backslash V(\mathbb{A})$ is zero, therefore this w contributes by zero. Hence we can restrict our summation over those $w\in W$ which satisfy $wMw^{-1} = M_1$. let us call this set W^{M,M_1}. But then

$$P_1^{(w)}(\mathbb{Q})\backslash P_1(\mathbb{Q}) = w^{-1}U_P(\mathbb{Q})w\cap U_{P_1}(\mathbb{Q})\backslash U_{P_1}(\mathbb{Q})$$

and the above expression becomes

$$\mathcal{F}^{P_1}\circ\ \mathrm{Eis}(\underline{\sigma},\underline{z})(f)(\underline{g}) = \textstyle\sum_{W_M\backslash W^{M,M_1}/W_M} \int_{U_{P_1}(\mathbb{Q})\backslash U_{P_1}(\mathbb{A})} \sum_{v\in U_{P_1}^{(w)}(\mathbb{Q})\backslash U_{P_1}(\mathbb{Q})} f_{\underline{z}}(wv\underline{u}\underline{g})d\underline{u} =$$

$$\textstyle\sum_{W_M\backslash W^M/W^{M,M_1}} \int_{(w^{-1}U_Pw\cap U_{P_1}\backslash U_{P_1})(\mathbb{A})} f_{\underline{z}}(w\underline{u}\underline{g})d\underline{u} \tag{9.52}$$

Our parabolic subgroup P contains the standard Borel subgroup, let U_P^- be the unipotent radical of the opposite group. In the argument of $f_{\underline{z}}$ we conjugate by w, then $U_P\cap wU_{P_1}w^{-1}\ \backslash wU_{P_1}w^{-1} = wU_{P_1}w^{-1}\cap U_P^- = U_{P,P_1}^{-,w}$.

$$\mathcal{F}^{P_1}\circ\ \mathrm{Eis}(\underline{\sigma},\underline{z})(f)(\underline{g}) = \sum_{W_{M_1}\backslash W^{M,M_1}/W_M} \int_{U_{P,P_1}^{-,w}(\mathbb{A})} f_{\underline{z}}(\underline{u}w\underline{g})d\underline{u} \tag{9.53}$$

We pick a w, the group M acts by the adjoint action on $w^{-1}U^{-,w}_{P,P_1}w$ and hence by a character $\delta^{(w)}_{P.P_1}$ on the highest exterior power of the Lie-algebra of this group. Then this operator sends

$$\mathcal{F}^{P_1,w} \circ \ \mathrm{Eis}(\underline{\sigma},\underline{z}) : I_P^G H_{\underline{\sigma}} \otimes |\gamma_P|^{\underline{z}} \to I_{P_1}^G H_{\underline{\sigma}^{w^{-1}}} \otimes (|\gamma_P|^{\underline{z}})^{w^{-1}} |\delta^{(w)}_{P.P_1}| \tag{9.54}$$

The integral is a product of local integrals over all places, we may assume that $f_{\underline{z}} = f_{\infty,\underline{z}} \prod_{p:prime} f_{p,\underline{z}}$. and then

$$\int_{U^{-,w}_{P,P_1}(\mathbb{A})} f_{\underline{z}}(\underline{u}w\underline{g})d\underline{u} = \int_{U^{-,w}_{P,P_1}(\mathbb{R})} f_{\infty,\underline{z}}(u_\infty w g_\infty) \prod_p \int_{U^{-,w}_{P,P_1}(\mathbb{Q}_p)} f_{p,\underline{z}}(u_p w g_p) \tag{9.55}$$

and here the local integrals yield intertwining operators

$$T_v^{P,P_1,w}(\sigma_v,\underline{z}) : I_P^G H_{\underline{\sigma}_v} \otimes |\gamma_P|_v^{\underline{z}} \to I_{P_1}^G H_{\underline{\sigma}_v^{w^{-1}}} \otimes |\gamma_P|_v^{w^{-1}\underline{z}} \otimes |\delta^{(w)}_{P.P_1}|_v \tag{9.56}$$

Proposition 9.4.1. *We can find local intertwining operators*

$$T_v^{P,P_1,w,\mathrm{loc}}(\sigma_v,\underline{z}) : I_P^G H_{\underline{\sigma}_v} \otimes |\gamma_P|_v^{\underline{z}} \to I_{P_1}^G H_{\underline{\sigma}_v^{w^{-1}}} \otimes |\gamma_P|_v^{w^{-1}\underline{z}} \otimes |\delta^{(w)}_{P.P_1}|_v \tag{9.57}$$

which have the following properties

a) They are holomorphic and nowhere zero in $\Re z_i \geq 0$ (we are still assuming that $\underline{\mu}$ is in the negative chamber.)

b) They have a certain rationality property (For the case of finite places see [Ha-Ra] 7.3.2.1, for the infinite places [Ha-HC])

c) At the unramified primes $v = p$ they map the spherical vector to the spherical vector.

and finally we have

$$\mathcal{F}^{P_1,w} \circ \ Eis(\underline{\sigma},\underline{z}) = C(w,P,P_1,\underline{\sigma},\underline{z})\, T_\infty^{P,P_1,w,\mathrm{loc}}(\sigma_\infty,\underline{z}) \otimes \bigotimes_{p:\mathrm{primes}}{}' \, T_p^{P,P_1,w,\mathrm{loc}}(\sigma_p,\underline{z}) \tag{9.58}$$

where $C(w,P,P_1,\underline{\sigma},\underline{z})$ is a meromorphic function in the variable $\underline{z}$. Therefore these functions $C(w,P,P_1,\underline{\sigma},\underline{z})$ decide whether $Eis(\underline{\sigma},\underline{z})$ is holomorphic at $\underline{z} = 0$, the poles of $Eis(\underline{\sigma},\underline{z})$ at $\underline{z}$ are the poles of the $C(w,P,P_1,\underline{\sigma},\underline{z})$.

We compute these factors $C(w,P,P_1,\underline{\sigma},\underline{z})$. By definition the group $U^{-,w}_{P,P_1}$ is a subgroup of U_P^- and as such it it easy to describe. Recall that our our group M is $\mathrm{Gl}_{n_1} \times \cdots \times \mathrm{Gl}_{n_r}$ and this corresponds to a decomposition of $\mathbb{Q}^n = X_1 \oplus X_2 \oplus \cdots \oplus X_r$ into subspaces and for any two indices $1 \leq i < j \leq r$ we define $G_{i,j}$ to be the subgroup $\mathrm{Gl}(X_i \oplus X_j)$ acting trivially on all other summands. For all pairs i,j we define the cocharacters $\chi_{i,j} : \mathbb{G}_m \to T$ where $\chi_{i,j}(t)$ is the diagonal matrix having t as entry at place i, and t^{-1} at place j and 1 everywhere else. We define $\mathbf{w}_{i,\mathrm{j}} :=< \chi_{i,j}, \underline{\mu}^{(1)} >$.

The intersection $G_{i,j} \cap U^{-,w}_{P,P_1}$ is either trivial or it is the full left lower block unipotent group $U^-_{i,i+1}$

This tells us that the above integral can be written as iterated integral over subgroups of the form $U_{\nu,\mu}(\mathbb{A})$. To be more precise: If $U^{-,w}_{P,P_1} \neq 1$ then we find an index i such that $U_{i,i+1}$ is not trivial. In a first step we compute the local integral $\int_{U_{i,i+1}(\mathbb{Q}_p)} f^{(0)}_{p,\underline{z}}(u_p w g_p) du_p$ at finite places where our representation $\underline{\sigma}_p$ unramified. We are basically in the situation, that our parabolic subgroup is maximal. The group $P' = P \cap G_{i,i+1}$ contains the standard Borel subgroup, $P'_1 = P_1 \cap G_{ii,i+1}$ is the opposite and $w = e$. Then

$$C_p(e, P', P'_1, \underline{\sigma}, \underline{z}) = \frac{L^{\mathrm{coh}}(\sigma_{i,p} \times \sigma^\vee_{i+1,p}, \frac{\mathbf{w}_{i,i+1}}{2} + b_i(w,\lambda) + < \chi_{i,i+1}, \underline{z} > -1)}{L^{\mathrm{coh}}(\sigma_{i,p} \times \sigma^\vee_{i+1,p}, \frac{\mathbf{w}_{i,i+1}}{2} + b_i(w,\lambda) + < \chi_{i,i+1}, \underline{z} >)} \tag{9.59}$$

A standard argument (See Langlands, Kim, Shahidi) tells us that we can reduce the computation of the iterated integral to situations like the one above and then we get at unramified places

$$C_p(w, P, P_1, \underline{\sigma}, \underline{z}) = \prod_{i,j} \frac{L^{\mathrm{coh}}(\sigma_{i,p} \times \sigma^\vee_{j,p}, \frac{\mathbf{w}_{i,j}}{2} + b_{i,j}(w,\lambda) + < \chi_{i,j}, \underline{z} > -1)}{L^{\mathrm{coh}}(\sigma_{i,p} \times \sigma^\vee_{j,p}, \frac{\mathbf{w}_{i,j}}{2} + b_{i,j}(w,\lambda) + < \chi_{i,j}, \underline{z} >} \tag{9.60}$$

Here the indices i, j run over those indices for which $U_{i,j} \subset U^{-,w}_{P,P_1}$, and $b_{i,j}(w,\lambda) =< \chi_{i,j}, \underline{\mu}^{\mathrm{ab}} >$.

Now we define $C_v(w, P, P_1, \underline{\sigma}, \underline{z})$ for all places v by the above expression, where we express the the cohomological L factor by the automorphic Rankin-Selberg L factor with the shift in the variable s. We go back to equation (9.58) and define

$$C(w, P, P_1, \underline{\sigma}, \underline{z}) = \prod_v C_v(w, P, P_1, \underline{\sigma}, \underline{z}). \tag{9.61}$$

We from the above proposition (9.4.1) that the factors $C(w, P, P_1, \underline{\sigma}, \underline{z})$ determine the analytic behavior of $Eis(\underline{\sigma}, \underline{z})$ at $\underline{z} = 0$. We have to exploit the analytic properties of the Rankin-Selberg L-functions. Here we have to use Shahidi's theorem which yields -(always remember that $\underline{\mu}$ is in the negative chamber-)

$$L^{\mathrm{coh}}(\sigma_{i,p} \times \sigma^\vee_{j,p}, \frac{\mathbf{w}_{i,j}}{2} + b_{i,j}(w,\lambda) + < \chi_{i,j}, \underline{z} > -1) \tag{9.62}$$

is holomorphic at $\underline{z} = 0$ unless we are in the following special case:

a) In the product in formula (9.60) we have factors $(i, i+1)$ where $n_i = n_{i+1}, \mu^{(1)}_i = \mu^{(1)}_{i+1}$ and $b_i(w,\lambda) = 1$.

b) The pair $\sigma_i \times \sigma_{i+1}$ is a segment, this means that $\sigma_i \otimes \det_i = \sigma_{i+1}$

If these two conditions are fulfilled then $C(w, P, P_1, \underline{\sigma}, \underline{z})$ has first order pole along $z_i = 0$.

The denominator is always holomorphic and never zero at $\underline{z} = 0$. (This is a deep theorem: it is the prime number theorem for Rankin-Selberg L-functions.)

9.4.1 Resume and questions

We see that we get an abundant supply of cohomology classes: Starting from any parabolic P and an isotypical subspace $\mathrm{Ind}_P^G H^{\bullet - l(w)}_{\mathrm{cusp}}(\mathcal{S}^M_{K_f^M}, \tilde{\mathcal{M}}_{w\cdot\lambda})(\underline{\sigma}_f)$ we get the Eisenstein intertwining operator (See equation (9.48)). We analyze what happens at $\underline{z} = 0$. If it is holomorphic we get a Hecke invariant homomorphism

$$\mathrm{Eis}^\bullet(0) : H^\bullet(\mathfrak{g}, K_\infty,\ \mathrm{Ind}_P^G \sigma_\infty \otimes \tilde{\mathcal{M}}) \otimes\ \mathrm{Ind}_P^G H_{\underline{\sigma}_f} \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\mathbb{C}}) \qquad (9.63)$$

We can restrict these cohomology classes to the boundary and even to boundary strata $\partial_Q(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ where Q runs over the parabolic subgroups associate to P, or more generally those parabolic subgroups which contain an associate to P. This means that the class "spreads out" over different boundary strata These restrictions to these other strata are given by certain linear maps which are product of "local intertwining operators" times certain special values of L functions.

In certain cases this "spreading out" is highly non trivial. We have to clarify some local issues. First of all we have to find out whether the local intertwining operators are non zero and have certain rationality properties. Especially we have to show that these local operators at the infinite places induce non zero maps between the cohomology groups of certain induced Harish-Chandra modules. And we have to show that these maps on the level of cohomology have rationality properties. ([Ha-HC] , [Ha-Ra], 7.3,)

If these local issues are settled then we can argue: The image of the cohomology $H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}})$ in the cohomology of the boundary is defined over $\mathbb{Q}$ (or some number field depending on our data). Since the $L-$ values enter in the description of this image we get rationality statements for special values of L-functions.

This has been exploited in some cases ([Ha-Gl2], [Ha-Gln], [Ha-Mum]) and the so far most general result in this direction is in [Ha-Ra] (See previous section).

But in case we have a pole we may also produce cohomology classes by taking residues, again starting from one boundary stratum. The restriction of these classes to the boundary will spread out over other strata in the boundary and we may play the same game. In this case the non vanishing issue of intertwining operators on cohomological level comes up again and will be discussed in the following section. (See Thm. 9.6.1)

We also will encounter situation where a pole along a plane $z_i = 0$ (or may be even several such planes) "fights" with a zero along some other planes containing zero. Then this influences the structure of the cohomology. But how? This question has been discussed in [Ha-Gln]. Is the order of vanishing along this zero visible in the structure of the cohomology? Or is it visible in the structure of the cohomology of the boundary, or in the spectral sequence?

9.5 Residual classes

We have seen that our Eisenstein classes may be singular at $\underline{z} = 0$. In this section we look at the extremal case that $\mathrm{Eis}(\sigma, \underline{z})$ has simple poles along the lines $z_i =< \chi_{n_i, n_i+1}, \underline{z} >= 0$, In this case we call these Eisenstein classes residual.

It follows from the work of Moeglin-Waldspurger [M-W] that this can only happen under some very special conditions.

We start from a factorization $n = uv$ we look the parabolic subgroup $P_{u,v}$ which contains the standard Borel subgroup and has reductive quotient $\mathrm{Gl}_u \times \mathrm{Gl}_u \times \cdots \times \mathrm{Gl}_u$. The standard maximal torus is a product $T = \prod_{i=1}^{i=v} T_i$ and accordingly we have $X^*(T) = \bigoplus_{i=1}^{i=v} X^*(T_i)$. We have an obvious identification $T_i = \mathbb{G}_m^u$.

We choose a highest weight $\lambda = \sum a_i\gamma_i + d\delta$, we assume that it is self dual, i.e. $a_i = a_{n-i}$. We have a restriction on the character $\underline{\mu} = w\cdot\lambda = w(\lambda+\rho_N)-\rho_N$, we must have

$$\begin{aligned} w(\lambda+\rho_N)-\rho_N = b_1\gamma_1^M + b_2\gamma_2^M + \cdots + b_{u-1}\gamma_{u-1}^M - (u+1)\gamma_u \\ +b_1\gamma_{1+u}^M + b_2\gamma_{2+u}^M + \cdots + b_{u-1}\gamma_{2u-1}^M - (u+1)\gamma_{2u} + \ldots \\ \ldots \\ b_1\gamma_{(v-1)u+1}^M + b_2\gamma_2^M + \cdots + b_{u-1}\gamma_{vu-1}^M + d\gamma_{uv} \end{aligned} \tag{9.64}$$

where $\gamma_{uv} = \delta = \det$. The highest weight is a sum $\underline{\mu} = \sum \mu_i$ where

$$\mu_i = \mu^{(1)} - d_i \mathrm{det}_i \text{ and } d_i - d_{i+1} = -1. \tag{9.65}$$

where the semi simple component $\mu^{(1)} = b_1\gamma_1^M + b_2\gamma_2^M + \cdots + b_{u-1}\gamma_{u-1}^M = b_1\gamma_{1+u}^M + b_2\gamma_{2+u}^M + \cdots + b_{u-1}\gamma_{2u-1}^M \ldots$ is "always the same". We notice that of course we have the self duality condition $b_i = b_{u-i}$. Furthermore we have $\sum d_i = -d$.

We define

$$\mathbb{D}_\mu = \bigotimes_{i=1}^{i=v} \mathbb{D}_{\mu_i} \tag{9.66}$$

and start from our isotypical $H^\bullet_{\mathrm{cusp}}(\mathcal{S}^M_{K_f^M}, \mathbb{D}_\mu \otimes \mathcal{M}_{w\cdot\lambda})(\sigma_f)$. The Künneth formula yields that we can write $\sigma_f = \sigma_{1,f} \times \sigma_{2,f} \times \cdots \times \sigma_{v,f}$ where all the $\sigma_{i,f}$ occur in the cuspidal cohomology of Gl_u, hence they may be compared. The relation (9.65) allows us to require that $\sigma_{i+1,f} = \sigma_{i,f} \otimes |\delta|$. If this is satisfied we say that σ_f is a segment. We assume $v \neq 1$ and hence $P \neq G$.

We know that under the assumption that σ_f is a segment (and only under this assumption) the factor $C(\sigma, w_P, \underline{z})$ has a simple poles along the lines $z_i = 0$, and this is the only term in (**??**) having these poles. The operator $T^{\mathrm{loc}}(\sigma, \underline{s})$ is a product of local operators at all places

$$T^{\mathrm{loc}}(\sigma, \underline{z}) = T^{\mathrm{loc}}_\infty(\sigma_\infty, \underline{s}) \times \prod_p T^{\mathrm{loc}}_p(\sigma_p, \underline{z}),$$

and the local factors are holomorphic as long as $\Re(z_i) \geq 0$. We take the residue at $\underline{z} = 0$ i.e. we evaluate

$$(\prod z_i)\mathcal{F}^P \circ \ \mathrm{Eis}(\sigma \otimes \underline{s})|_{\underline{z}=0} = (\prod z_i) C(\sigma, w_P, \underline{z})|_{\underline{z}=0} T^{\mathrm{loc}}(\sigma, w_P, \underline{0})(f) \tag{9.67}$$

This tells us that the residue of the Eisenstein class gives us an intertwining operator

$$\mathrm{Res}_{\underline{z}=0}\ \mathrm{Eis}(\sigma\otimes\underline{z}) : {}^{\mathrm{a}}\mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_\mu\otimes V_{\sigma_f}\to L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f,\omega^{-1}_{\mathcal{M}_\lambda}|_{S(\mathbb{R})^0}) \tag{9.68}$$

The image $J_{\sigma_\infty}\otimes J_{\sigma_f}$ is an irreducible module (this is a Langlands quotient) and via the constant Fourier coefficient it injects into ${}^{\mathrm{a}}\mathrm{Ind}_{P(\mathbb{A}))}^{G(\mathbb{A})}\mathbb{D}_{\mu'}\otimes V_{\sigma_f}$. At the infinite place we get a diagram

$$\begin{array}{ccc} \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_\mu & \xrightarrow{T^{(\mathrm{loc})}(D_\mu)} & J_{\sigma_\infty} \\ & & \downarrow \\ & & \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_{\mu'} \end{array} \tag{9.69}$$

It is a - not completely trivial - exercise to write down the solutions for the system of equations (9.64). We start from a highest weight of a special form

$$\lambda = a_1\gamma_u + a_2\gamma_{2u}+\cdots+a_{v-1}\gamma_{(v-1)u}+d\delta \tag{9.70}$$

which in addition is essentially self dual, i.e. $a_i = a_{v-i}$ the number d is uninteresting and only serves to satisfy the parity condition.

We choose a specific Kostant representative $w'_{u,v}\in W^P$ whose τ- it is the permutation in the letters $1,2,\dots,n$ given by the following rule: write $\nu = i+(j-1)v$ with $1\le i\le u$ then $w'_{u,v}(\nu) = j+(i-1)v$. Then we compute $w'_{u,v}(\lambda+\rho_N)-\rho_N\in X^*(T\times E)$ and we get

$$\begin{gathered}(w'_{u,v}(\lambda+\rho_N)-\rho_N) = \\ (a_1+v-1)\gamma_1^M+(a_2+v-1)\gamma_2^M+(a_{u-1}+v-1)\gamma_{u-1}^M \\ (a_1+v-1)\gamma_{1+u}^M+(a_2+v-1)\gamma_{2+u}^M+(a_{u-1}+v-1)\gamma_{u-1+u}^M \\ \vdots \\ (a_1+v-1)\gamma_{1+(v-1)u}^M+(a_2+v-1)\gamma_{2+(v-1)u}^M+\cdots+(a_{u-1}+v-1)\gamma_{u-1+(v-1)u}^M)+ \\ -(u-1)(\gamma_u+\gamma_{2u}+\cdots+\gamma_{(v-1)u})+d\delta\end{gathered} \tag{9.71}$$

The length of this Kostant representative is

$$l(w'_{u,v}) = n(u-1)(v-1)/4.$$

Let w_P be the longest Kostant representative which sends all the roots in U_P to negative roots. Then we define the (reflected) Kostant representative $w_{u,v} = w_Pw'_{u,v}$. We get

$$\begin{aligned} w_{u,v}(\lambda+\rho)-\rho=\mu = (a_1+v-1)(\gamma_1^M+\gamma_{1+u}^M+\cdots+\gamma_{1+(v-1)u}^M)+ \\ (a_2+v-1)(\gamma_2^M+\gamma_{2+u}^M+\cdots+\gamma_{2+(v-1)u}^M)+ \\ \vdots \\ (a_{u-1}+v-1)(\gamma_{u-1}^M+\gamma_{u-1+u}^M+\cdots+\gamma_{u-1+(v-1)u}^M)+ \\ -(u+1)(\gamma_u+\gamma_{2u}+\cdots+\gamma_{(v-1)u})+d\delta. \end{aligned} \tag{9.72}$$

Hence we see that we the semi simple component stays the same and the abelian parts differ by $2(\gamma_u+\gamma_{2u}+\cdots+\gamma_{(v-1)u})$) We see that we can solve (9.64) provided $b_i\ge v-1$.

The identification $J_{\sigma_\infty} \xrightarrow{\sim} A_{\mathfrak{q}}(\lambda))$

Of course we expect

$$H^\bullet(\mathfrak{g}, K_\infty, J_{\sigma_\infty} \otimes \mathcal{M}_\lambda) \neq 0. \tag{9.73}$$

In the paper [Vo-Zu] the authors give a list of irreducible $(\mathfrak{g}, K_\infty)$ modules $A_{\mathfrak{q}}(\lambda)$ which have non trivial cohomology $H^\bullet(\mathfrak{g}, K_\infty, A_{\mathfrak{q}}(\lambda)\otimes\mathcal{M}_\lambda) \neq 0$. This list contains all unitary modules having this property. On the other hand we know that any such unitary $A_{\mathfrak{q}}(\lambda)$ can be written as a Langlands quotient. In the paper of Vogan and Zuckerman it is explained how we can get a given unitary $A_{\mathfrak{q}}(\lambda)$ as Langlands quotient, basically this means we construct a diagram of the form (9.69) but where now we have $A_{\mathfrak{q}}(\lambda)$ in the upper right corner instead of J_{σ_∞}. In the following section we describe a specific $A_{\mathfrak{q}}(\lambda)$ and write it as a Langlands quotient (i.e. we find its Langlands parameters) this means we determine the upper left and lower right entries and then check that these entries are the ones in diagram (9.69). From this we will derive the following

The map

$$H^\bullet(\mathfrak{g}, K_\infty, J_{\sigma_\infty} \otimes \mathcal{M}_\lambda) \otimes J_{\sigma_f} \to H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda) \tag{9.74}$$

is non zero in degree $l(w'_{u,v}) = n(u-1)(v-1)/4$.

See Theorem (9.6.1)

9.6 Detour: $(\mathfrak{g}, K_\infty)-$ modules with cohomology for $G = \mathrm{Gl}_n$

I want to fix some notations and conventions.

Let $T/\mathbb{Q}$ be the maximal torus in $\mathrm{Gl}_n/\mathbb{Q}$, let $T^{(1)} = Sl_n \cap T$. We put $r = n-1$. We have the standard basis for the character-module $X^*(T)$:

$$e_i : T \to G_m, t \mapsto t_i.$$

The positive (resp. simple roots) roots are $\alpha_{i,j} = e_i - e_j, i < j$, (resp. $\alpha_i = e_i - e_{i+1}$.) We have the determinant $\delta = \sum_1^n e_i$.

The fundamental weights are elements in $X^*(T) \otimes \mathbb{Q}$, they are defined by

$$\gamma_i = \sum_{\nu=1}^{i} e_\nu - \frac{i}{n}\delta,$$

these γ_i are the fundamental weights if we restrict to Sl_n, the image of γ_i under the restriction map lies in $X^*(T^{(1)})$.

From now on my natural basis for $X^*(T) \otimes \mathbb{Q}$ will be

$$\{\gamma_1, \ldots, \gamma_i, \ldots, \gamma_r, \delta\}.$$

This basis respects the decomposition of T into $T^{(1)} \cdot G_m$, the first factor is its component in Sl_n and the second one is the central torus.

We also have the cocharacters $\chi_i \in X_*(T^{(1)})$ which are given by

$$\chi_i : t \mapsto \begin{pmatrix} 1 & 0 & 0 & & \dots & 0 \\ 0 & \ddots & \dots & \dots & \dots & \dots \\ 0 & 0 & t & 0 & \dots & 0 \\ 0 & \dots & 0 & t^{-1} & \dots & 0 \\ \dots & \dots & \dots & & \ddots & \dots \\ 0 & 0 & 0 & \dots & 0 & 1 \end{pmatrix}$$

and the central cocharacter

$$\zeta : t \mapsto \begin{pmatrix} t & 0 & 0\dots & 0 \\ 0 & t & \dots & \dots \\ 0 & 0 & \ddots & \dots \\ 0 & \dots & 0 & \end{pmatrix}$$

We have the standard pairing $(\chi, \gamma) \mapsto < \chi, \gamma >$ between cocharacters and characters which is defined by $\gamma \circ \chi = \{t \mapsto t^{<\chi,\gamma>}\}$. We have the relations

$$< \chi_j, \gamma_i >= \delta_{ij}, \ < \chi_i, \alpha_i >= 2$$

the character δ is trivial on the χ_i and $\delta \circ \zeta = \{t \mapsto t^n\}$. It is clear that an element $\gamma = \sum_i a_i\gamma_i + d\delta \in X^*(T)$ if and only if the $a_i, nd \in \mathbb{Z}$ and we have the congruence

$$\sum ia_i \equiv nd \mod n.$$

We identify the center of Gl_n with G_m via the cocharacter ζ, the character module of G_m is $\mathbb{Z}$. Hence the central character ω_λ is an integer and we find

$$\omega_\lambda = nd.$$

Actually this central character should be considered as an element in $\mathbb{Z} \mod n$ because we can replace d by $r + d$ and then the central character changes by a multiply of n. If $\lambda \in X^+(T^{(1)})$ is a dominant weight then we write it as

$$\lambda = \sum a_i\gamma_i$$

then we have $a_i \geq 0$.

9.6.1 The tempered representation at infinity

We consider the group $\mathrm{Gl}_n/\mathbb{R}$, we choose a essentially selfdual highest weight $\lambda = \sum_1^{n-1} a_i\gamma_i + d\delta($ i.e. $a_i = a_{n-i})$. The a_i are integers and d is a half integer which satisfies the parity condition

$$d \in \mathbb{Z} \text{ if } n \text{ is odd }, \frac{n}{2} a_{\frac{n}{2}} \equiv nd \mod n \text{ if } n \text{ is even}$$

We want to recall the construction of a specific $(\mathfrak{g}, K_\infty)$ -module $\mathbb{D}_\lambda$ such that

$$H^\bullet(\mathfrak{g}, K_\infty, \mathbb{D}_\lambda \otimes \mathcal{M}_\lambda) \neq 0$$

and we will also determine the structure of this cohomology. This module is the only tempered Harish-Chandra module which has non trivial cohomology with coefficients in $\mathcal{M}_\lambda$. The center $\mathbb{G}_m$ of Gl_n acts on the module $\mathcal{M}_\lambda$ by the character $\omega_\lambda : x \mapsto x^{nd}$. Since we want no zero cohomology the center $S(\mathbb{R})$ of $\mathrm{Gl}_n(\mathbb{R})$ acts by the central character $(\omega_\lambda)_{\mathbb{R}}^{-1}$ on $\mathbb{D}_\lambda$. The module $\mathbb{D}_\lambda$ will be essentially unitary with respect to that character.

We construct our representation $\mathbb{D}_\lambda$ by inducing from discrete series representations. We consider the parabolic subgroup ${}^\circ P$ whose simple root system is described by the diagram

$$\circ - \times - \circ - \times - \cdots - \circ(-\times) \tag{9.75}$$

i.e. the set of simple roots $I_{{}^\circ M}$ of the semi simple part of the Levi quotient ${}^\circ M$ is consists of those which have an odd index. Let m be the largest odd integer less or equal to $n-1$ then α_m is the last root in the system of simple roots in $I_{{}^\circ M}$. Of course $m = n-1$ if n is even and $m = n-2$ else.

The reductive quotient is equal to $\mathrm{Gl}_2 \times \mathrm{Gl}_2 \times \ldots \mathrm{Gl}_2(\times \mathbb{G}_m)$, where the last factor occurs if n is odd. This product decomposition of ${}^\circ M$ induces a product decomposition of the standard maximal torus $T = \prod_{i:i\text{odd}} T_i(\times \mathbb{G}_m)$ and for the character module we get

$$X^*(T) = \bigoplus_{i:i\text{odd}} X^*(T_i)(\oplus X^*(\mathbb{G}_m)) \tag{9.76}$$

The semi simple reductive quotient ${}^\circ M^{(1)}(\mathbb{R})$ is $A_1 \times A_1 \times \cdots \times A_1$, the number of factors is

$${}^\circ r = (m+1)/2 = \begin{cases} \frac{n}{2} & \text{if n is even} \\ \frac{n-1}{2} & \text{if } n \text{ is odd} \end{cases}$$

We also introduce the number

$$\epsilon(n) = \begin{cases} 0 & \text{if } n \text{ even} \\ 1 & \text{if } n \text{ odd} \end{cases} \tag{9.77}$$

We have a very specific Kostant representative $w_{\mathrm{un}} \in W^{{}^\circ P}$. The inverse of this permutation it is given by

$$w_{\mathrm{un}}^{-1} = \{1 \mapsto 1, 2 \mapsto n, 3 \mapsto 2, 4 \mapsto n-1 \ldots\}.$$

The length of this element is equal to $1/2$ the number of roots in the unipotent radical of ${}^\circ P$, i.e.

$$l(w_{\mathrm{un}}) = \begin{cases} \frac{1}{4}n(n-2) & \text{if } n \text{ is even} \\ \\ \frac{1}{4}(n-1)^2 & \text{if } n \text{ is odd} \end{cases} \tag{9.78}$$

We compute

$$w_{\mathrm{un}}(\lambda+\rho) - \rho = \sum_{i:i \text{ odd}} b_i \gamma_i^{{}^\circ M^{(1)}} + d\delta = \sum_{i:i \text{ odd}} b_i \frac{\alpha_i}{2} + d\delta = \tilde{\mu}^{(1)} + d\delta. \tag{9.79}$$

(The subscript $_{\mathrm{un}}$ refers to unitary, it refers also to the length being half the dimension of the unipotent radical. Here we have to observe that $w \cdot \lambda$ is an element in $X^*(T)$ but the individual summands may only lie in $X^*(T) \otimes \mathbb{Q} = X^*_{\mathbb{Q}}(T)$. Any element $\gamma \in X^*(T)$ also defines a quasicharacter $\gamma_{\mathbb{R}} : T(\mathbb{R}) \to \mathbb{R}^\times$ (by definition). But an element $\gamma \in X^*_{\mathbb{Q}}(T)$ only defines a quasicharacter $|\gamma|_{\mathbb{R}} : T(\mathbb{R}) \to \mathbb{R}^\times_{>0}$ which is defined by $|\gamma|_{\mathbb{R}}(x) = |m\gamma(x)|^{1/m}$.)

To compute the coefficients b_j we use the pairing (See7.1) and observe that $< \chi_i, \gamma_j >= \delta_{i,j}$. Then

$$b_j =< \chi_j, w_{\mathrm{un}}(\lambda+\rho) - \rho >=< w_{\mathrm{un}}^{-1}\chi_j, \lambda+\rho > - < \chi_j, \rho > . \tag{9.80}$$

Now the choice of w_{un} becomes clear. It is designed in such a way that

$$w_{\mathrm{un}}^{-1}\chi_1(t) = \begin{pmatrix} t & 0 & 0 & & \dots & 0 \\ 0 & \ddots & \dots & \dots & \dots & \dots \\ 0 & 0 & 1 & 0 & \dots & 0 \\ 0 & \dots & 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & & \ddots & 0 \\ 0 & 0 & 0 & \dots & 0 & t^{-1} \end{pmatrix}, w_{\mathrm{un}}^{-1}\chi_3(t) = \begin{pmatrix} 1 & 0 & 0 & & \dots & 0 \\ 0 & t & \dots & \dots & \dots & \dots \\ 0 & 0 & 1 & 0 & \dots & 0 \\ 0 & \dots & 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & & t^{-1} & 0 \\ 0 & 0 & 0 & \dots & 0 & 1 \end{pmatrix}$$

and for the general odd index j we have $w_{\mathrm{un}}^{-1}\chi_j(t) = h_{(j+1)/2}$ where for all $1 \le \nu \le n/2$ we denote by $h_\nu(t)$ the diagonal matrix which has a 1 at all entries different from $\nu, n+1-\nu$ and which has entry t at ν and t^{-1} at $n+1-\nu$. Then $h_\nu = \{t \mapsto h_\nu(t)\}$ is a cocharacter. It is clear that

$$\gamma_i(h_\nu(t)) = \begin{cases} t & \text{if } \nu \le i \le n-\nu \\ 1 & \text{else} \end{cases}$$

This yields for $j = 1, \dots, {}^\circ r$

$$b_{2j-1} = \sum_\nu (a_\nu+1) < h_j, \gamma_\nu > - < \chi_j, \rho >= (\sum_{j \le \nu \le n-j} (a_\nu+1)) - 1.$$

We should keep in mind that we assume $a_\nu = a_{n-\nu}$. Then we can rewrite the expressions for the b_ν :

$$b_{2j-1} = \begin{cases} 2a_j + 2a_{j+1} + \dots + 2a_{\frac{n}{2}-1} + a_{\frac{n}{2}} + n - 2j & \text{if } n \text{ is even} \\ 2a_j + 2a_{j+1} + \dots + 2a_{\frac{n-1}{2}} + n - 2j & \text{if } n \text{ is odd} \end{cases} \tag{9.81}$$

The b_{2j+1} will be called the *cuspidal parameters* and we summarize

The b_{2j-1} have the same parity, this parity is odd if n is odd. If n is even then b_{2j-1} has parity of $a_{\frac{n}{2}}$. We have $b_1 > b_3 > \dots > b_m > 0$. They only depend on the semi simple part $\lambda^{(1)}$.

By Kostants theorem

$$w_{\mathrm{un}} \cdot \lambda = w_{\mathrm{un}}(\lambda+\rho) - \rho$$

is the highest weight of an irreducible representation of ${}^\circ M$. This irreducible representation occurs with multiplicity one in $H^{l(w_{\rm un})}(\mathfrak{u}_{{}^\circ P},\mathcal{M}_\lambda)$.

The highest weight of this representation is

$$w_{\rm un}\cdot\lambda = w_{\rm un}(\lambda+\rho)-\rho = \sum_{i:i \text{ odd}} b_i\gamma_i^{{}^\circ M^{(1)}} + d\delta - (2\gamma_2+2\gamma_4+\cdots+2\gamma_{m-1}+\frac{3}{2}\gamma_{m+1}) \tag{9.82}$$

Digression: *Discrete series representations of* $\mathrm{Gl}_2(\mathbb{R})$*, some conventions*

We consider the group $\mathrm{Gl}_2/\operatorname{Spec}(\mathbb{Z})$, the standard torus T and the standard Borel subgroup B. We have $X^*(T)=\{\gamma = a\gamma_1+d\delta | a\in\mathbb{Z}, d\in\frac{1}{2}\mathbb{Z}; a+2d\equiv 0 \mod 2\}$ where

$$\gamma(\begin{pmatrix} t_1 & 0\\ 0 & t_2\end{pmatrix}) = t_1^{\frac{a}{2}+d}t_2^{-\frac{a}{2}+d} = (\frac{t_1}{t_2})^{\frac{a}{2}}(t_1t_2)^d$$

(Note that the exponents in the expression in the middle term are integers)

A dominant weight $\lambda = a\gamma_1+d\delta$ is a character where $a\geq 0$. These dominant weights parameterize the finite dimensional representations of $\mathrm{Gl}_2/\mathbb{Q}$. The dual representation is given by $\lambda^\vee = a\gamma_1 - d\delta$. But these highest weights also parameterize the discrete series representations of $\mathrm{Gl}_2(\mathbb{R})$, (or better the discrete series Harish-Chandra modules). The highest weight λ defines a line bundle $\mathcal{L}_{-a\gamma+d\delta}$ on $B\backslash G$ and

$$\mathcal{M}_\lambda = H^0(B\backslash G, \mathcal{L}_{-a\gamma+d\delta})$$

Then we get an embedding and a resulting exact sequence

$$0\to\mathcal{M}_\lambda\to I_B^G((-a\gamma_1+d\delta)_{\mathbb{R}})\to\mathcal{D}_{\lambda^\vee}\to 0$$

and $\mathcal{D}_{\lambda^\vee}$ is the discrete series representation attached to $\lambda^\vee$. (Note the subscript $_{\mathbb{R}}$ can not be pulled inside the bracket!).

A basic argument in representation theory yields a pairing

$$I_B^G((-a\gamma_1-d\delta)_{\mathbb{R}})\times I_B^G(((a+2)\gamma_1+d\delta)_{\mathbb{R}})\to\mathbb{R}$$

(here observe that $2\gamma_1 = 2\rho\in X^*(T)$).

From this we get another exact sequence which gives the more familiar definition of the discrete series representation

$$0\to\mathcal{D}_\lambda\to I_B^G(((a+2)\gamma_1+d\delta)_{\mathbb{R}})\to\mathcal{M}_\lambda\to 0. \tag{9.83}$$

The module $\mathbb{D}_\lambda$ is also a module for the group $K_\infty = \mathrm{SO}(2)$ and it is well known that it decomposes into K_∞ types

$$D_\lambda = \cdots\oplus\mathbb{C}\psi_\nu\ldots\mathbb{C}\psi_{-a-4}\oplus\mathbb{C}\psi_{-a-2}\oplus\mathbb{C}\psi_{+a+2}\oplus\mathbb{C}\psi_{a+4}\ldots \tag{9.84}$$

(End of digression)

We return to our formula (9.82). The group

$${}^\circ M = \prod_{i:i\text{odd}} M_i\times(\mathbb{G}_m)$$

where $M_i = \mathrm{Gl}_2$. If T_i is the maximal torus in the i-th factor, then the highest weight is $\gamma_i^{\circ M^{(1)}}$ and let δ_i be the determinant on that factor. The indices i run over the odd numbers $1, 3, \dots, m$. If n is odd then let $\delta_n : T \to \mathbb{G}_m$ be the character given by the last entry. Then we have for the determinant

$$\delta = \delta_1 + \delta_3 + \cdots + \delta_m + \begin{cases} 0 \\ \delta_n \end{cases} \tag{9.85}$$

We want to write the character $2\gamma_2 + 2\gamma_4 + \cdots + 2\gamma_{m-1} + \frac{3}{2}\gamma_{m+1}$ in terms of the δ_i. We recall that

$$\begin{array}{c} \gamma_2 = \delta_1 - \frac{2}{n}\delta \\ \gamma_4 = \delta_1 + \delta_3 - \frac{4}{n}\delta \\ \vdots \\ \gamma_{m-1} = \delta_1 + \delta_3 \cdots + \delta_{m-2} - \frac{m-1}{n}\delta \\ \text{and if } n \text{ is odd} \\ \gamma_{m+1} = \delta_1 + \delta_3 \cdots + \delta_m - \frac{m+1}{n}\delta \end{array} \tag{9.86}$$

Then the summation over the δ-terms on the right hand side yields

$$-\frac{1}{n}(4 + 8 + \cdots + 2(m-1) - \begin{cases} 0 \\ \frac{3}{2}(m+1) \end{cases}) = -[\frac{n-1}{2}] \tag{9.87}$$

and if we take our formula (9.85) into account and also count the number of times a δ_i occurs in the summation we get

$$2\gamma_2 + 2\gamma_4 + \cdots + 2\gamma_{m-1} + \frac{3}{2}\gamma_{m+1} = \begin{cases} (\frac{n}{2} - 1)\delta_1 + (\frac{n}{2} - 3)\delta_3 + \cdots + (-\frac{n}{2} + 1)\delta_{m-2} & n \equiv 0 \mod 2 \\ \frac{n-2}{2}\delta_1 + \cdots + \frac{-n+4}{2}\delta_m - \frac{n-1}{2}\delta_n & \text{else} \end{cases} \tag{9.88}$$

Let us denote the coefficient of δ_i in the expressions on the right hand side by $c(i, n.)$ We recall that we still have the summand $d\delta$ in our formula (**??**. Then

$$\underline{\mu} = w_{\mathrm{un}} \cdot \lambda = \sum_{i:i \text{ odd}} b_i \gamma_i^{\circ M^{(1)}} + (c(i,n) + d)\delta_i + \begin{cases} d\delta \\ (-\frac{n-1}{2} + d)\delta_n \end{cases} \tag{9.89}$$

We claim that the individual summands are in the character modules $X^*(T_i)$ (resp. $X^*(\mathbb{G}_m)$). This means that

$$b_i \gamma_i^{\circ M^{(1)}} + (c(i,n) + d)\delta_i \in X^*(T_i),\ -\frac{n-1}{2} + d \in \mathbb{Z}. \tag{9.90}$$

We have to verify the parity conditions. If n is odd the the parity condition for λ says that $d \in \mathbb{Z}$. On the other hand we know that in this case the b_i are odd and since the $c(i,n)$ are also odd the parity condition is satisfied for the individual summands.

If n is even then the parity condition for for λ says that $\frac{n}{2} a_{\frac{n}{2}} \equiv nd \mod n$. We know that the b_i all have the same parity: $b_i \equiv a_{\frac{n}{2}} \mod 2$. Hence need that $a_{\frac{n}{2}} \equiv 2d \mod 2$, but this is the parity condition for λ.

For any of the characters μ_i we have the induced representations $I_{B_i}^{\circ M_i}(\mu_i + 2\rho_i)$ the discrete series representation $\mathcal{D}_{\mu_i}$ and the exact sequence

$$0 \to \mathcal{D}_{\mu_i} \to I_{B_i}^{\circ M_i}(\mu_i + 2\rho_i) \to \mathcal{M}_{\mu_i} \to 0. \tag{9.91}$$

The tensor product

$$\mathcal{D}_\mu = \bigotimes_{i:i\text{odd}} \mathcal{D}_{\mu_i} \otimes \mathbb{C}(-\frac{n-1}{2} + d) \tag{9.92}$$

is a module for ${}^\circ M$.

Here we have to work with $K_\infty^{\circ M} = K_\infty \cap^\circ M$. This compact group is not necessarily connected, its connected component of the identity is

$$K_\infty^{\circ M} \cap^\circ M^{(1)}(\mathbb{R}) = \mathrm{SO}(2) \times \mathrm{SO}(2) \times \cdots \times \mathrm{SO}(2) = K_\infty^{\circ M,(1)}.$$

An easy computation shows

$$K_\infty^{\circ M} = \begin{cases} S(\mathrm{O}(2) \times \mathrm{O}(2) \times \cdots \times \mathrm{O}(2)) & \text{if } n \text{ is even} \\ \mathrm{O}(2) \times \mathrm{O}(2) \times \cdots \times \mathrm{O}(2) & \text{if } n \text{ is odd} \end{cases}, \tag{9.93}$$

since $K_\infty \subset \mathrm{Sl}_n(\mathbb{R})$ we have the determinant condition in the even case, in the odd case we have the $\{\pm 1\}$ in the last factor and this relaxes the determinant condition.

Under the action of $K_\infty^{\circ M,(1)}$ we get a decomposition

$$\mathcal{D}_{\underline{\mu}} = \bigoplus_{\underline{\varepsilon}} \bigotimes_{i=1}^{\circ r} (\bigoplus_{\nu_i=0}^{\infty} \mathbb{C}\psi_{\varepsilon_i(b_i+2+2\nu_i)}) \tag{9.94}$$

occur with multiplicity one. Here $\underline{\varepsilon} = (\dots, \varepsilon_i, \dots)$ is an array of signs ± 1.

The induced representation (algebraic induction)

$$\mathrm{Ind}_{{}^\circ P(\mathbb{R})}^{G(\mathbb{R})} \mathcal{D}_{\underline{\mu}} = \mathbb{D}_\lambda \tag{9.95}$$

is an irreducible essentially unitary $(\mathfrak{g}, K_\infty)$ -module, this is the module we wanted to construct. (To be more precise: We first construct the induced representation of $G(\mathbb{R})$ where $G(\mathbb{R})$ is acting on vectors space V_∞ consisting of a suitable class of functions from $G(\mathbb{R})$ with values in $\mathcal{D}_{\underline{\mu}}$ and then we take the K_∞ finite vectors in V_∞.) The restriction of this module to $K_\infty^{(1)}$ s given by

$$\mathrm{Ind}_{K_\infty^{\circ M^{(1)}}}^{K_\infty^{(1)}} \mathcal{D}_{\underline{\mu}} = \bigoplus_{\underline{\varepsilon}} \bigotimes_{i=1}^{\circ r} (\bigoplus_{\nu_i=0}^{\infty} \mathrm{Ind}_{K_\infty^{\circ M^{(1)}}}^{K_\infty^{(1)}} \mathbb{C}\psi_{\varepsilon_i(b_i+2+2\nu_i)}) \tag{9.96}$$

(The last induced module is defined in terms of the theory of algebraic groups. We consider $K_\infty^{(1)}$ as the group of real points of an algebraic group, namely the connected group of the identity of the fixed points under the Cartan involution Θ. Then $K_\infty^{\circ M^{(1)}}$ is the group of real points of a maximal torus. Then

$$\mathrm{Ind}_{K_\infty^{\circ M^{(1)}}}^{K_\infty^{(1)}} \mathbb{C}\psi_{\varepsilon_i(b_i+2+2\nu_i)} =$$
$$\{f | f \text{ regular function } f(tk) = \prod_j e_i(t)^{\varepsilon_i(b_i+2+2\nu_i)} f(k), \text{ for all } t \in K_\infty^{\circ M^{(1)}}, k \in K_\infty\} \tag{9.97}$$

)

We compute the cohomology of this module

$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ D_\lambda \otimes \mathcal{M}_\lambda) = H^\bullet(\mathfrak{g}, K_\infty,\ D_\lambda \otimes \mathcal{M}_\lambda),$$

i.e. the differentials in the complex on the left hand side are all zero. (Reference to 4.1.4)

We apply Delorme to compute this cohomology. We can decompose ${}^\circ\mathfrak{m} ={}^\circ \mathfrak{m}^{(1)} \oplus \mathfrak{a}$ then ${}^\circ\mathfrak{k} \subset^\circ \mathfrak{m}^{(1)}$ and

$$\begin{aligned}\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ D_\lambda \otimes \mathcal{M}_\lambda) = \ & \mathrm{Hom}_{K_\infty^{\circ M}}(\Lambda^\bullet({}^\circ\mathfrak{m}/{}^\circ\mathfrak{k}), \mathcal{D}_{\tilde{\mu}} \otimes \mathcal{M}_{w_{\mathrm{un}}\cdot\lambda}) = \\ & \mathrm{Hom}_{K_\infty^{\circ M}}(\Lambda^\bullet({}^\circ\mathfrak{m}^{(1)}/{}^\circ\mathfrak{k}), \mathcal{D}_{\tilde{\mu}} \otimes \mathcal{M}_{w_{\mathrm{un}}\cdot\lambda}) \otimes \Lambda^\bullet(\mathfrak{a}).\end{aligned} \tag{9.98}$$

If we replace $K_\infty^{\circ M}$ on the right hand side by its connected component of the identity then we have an obvious decomposition

$$\mathrm{Hom}_{K_\infty^{\circ M,(1)}}(\Lambda^\bullet({}^\circ\mathfrak{m}^{(1)}/{}^\circ\mathfrak{k}), \mathcal{D}_\mu \otimes \mathcal{M}_{w_{\mathrm{un}}\cdot\lambda}) = \bigotimes_{i:i \text{ odd}} \mathrm{Hom}_{K_\infty^{i,{}^\circ M,(1)}}(\Lambda^\bullet({}^\circ\mathfrak{m}^{(i,1)}/{}^\circ\mathfrak{k}^i), \mathcal{D}_{b_i} \otimes \mathcal{M}_{b_i}) \tag{9.99}$$

the factors on the right hand side are of rank two: We have $K_\infty^{i,{}^\circ M,(1)} = \mathrm{SO}(2)$ and under the adjoint action of $K_\infty^{i,{}^\circ M,(1)}$ the module $\mathfrak{m}^{(i,1)}/{}^\circ\mathfrak{k}^i \otimes \mathbb{C}$ decomposes

$$\mathfrak{m}^{(i,1)}/{}^\circ\mathfrak{k}^i \otimes \mathbb{C} = \mathbb{C}P_{i,+}^\vee \oplus \mathbb{C}P_{i,-}^\vee$$

(See [Sltwo.pdf]) Then the two summands are generated by the tensors

$$\omega_{i,+} = P_{i,+}^\vee \otimes \psi_{b_i+2} \otimes m_{-b_i}, \bar{\omega}_{i,-} = P_{i,-}^\vee \otimes \psi_{-b_-2} \otimes m_{b_i} \tag{9.100}$$

where $m_{\pm(b_i)}$ is a highest (resp.) lowest weight vector for $K_\infty^{i,{}^\circ M}$ acting on $\mathcal{M}_{w_{\mathrm{un}}\cdot\lambda}$. On the tensor product on the right we have an action of the maximal compact subgroup $\mathrm{O}(2) \times \mathrm{O}(2) \times \cdots \times \mathrm{O}(2)$ and under this action it decomposes into eigenspaces of dimension one. These eigenspaces are given by the product of sign characters $\underline{\epsilon} = (\epsilon_1, \epsilon_2, \dots)$.

Then it becomes clear that $\mathrm{Hom}_{K_\infty^{\circ M}}(\Lambda^\bullet({}^\circ\mathfrak{m}^{(1)}/{}^\circ\mathfrak{k}), \mathcal{D}_{\underline{\mu}} \otimes \mathcal{M}_{w_{\mathrm{un}}\cdot\lambda})$ is of rank one if n is odd and for n even it decomposes into two eigenspaces for the action of the group $\mathrm{O}(2) \times \mathrm{O}(2) \times \cdots \times \mathrm{O}(2)/S(\mathrm{O}(2) \times \mathrm{O}(2) \times \cdots \times \mathrm{O}(2)) = \{\pm 1\}$

$$\mathrm{Hom}_{K_\infty^{\circ M}}(\Lambda^\bullet({}^\circ\mathfrak{m}^{(1)}/{}^\circ\mathfrak{k}), \mathcal{D}_{\underline{\mu}} \otimes \mathcal{M}_{w_{\mathrm{un}}\cdot\lambda}) =$$

$$\mathrm{Hom}_{K_\infty^{\circ M}}(\Lambda^\bullet({}^\circ\mathfrak{m}^{(1)}/{}^\circ\mathfrak{k}), \mathcal{D}_{\underline{\mu}} \otimes \mathcal{M}_{w_{\mathrm{un}}\cdot\lambda}))_+ \oplus\ \mathrm{Hom}_{K_\infty^{\circ M}}(\Lambda^\bullet({}^\circ\mathfrak{m}^{(1)}/{}^\circ\mathfrak{k}), \mathcal{D}_{\underline{\mu}} \otimes \mathcal{M}_{w_{\mathrm{un}}\cdot\lambda}))_-$$

We have to recall that $\mathcal{M}_{\lambda^{\mathrm{un}}_{{}^\circ M}} = H^{l(w_{\mathrm{un}})}(\mathfrak{u}_{{}^\circ P}, \mathcal{M}_\lambda)$ is a cohomology group in degree $l(w_{\mathrm{un}})$. The classes in the factors of the last tensor product lie in degree 1, hence the multiply up to classes in degree ${}^\circ r$. This means that

$$H^q(\mathfrak{g}, K_\infty, \mathbb{D}_\lambda \otimes \mathcal{M}_\lambda) \neq 0 \text{ exactly for } q \in [l(w_{\mathrm{un}}) +^\circ r, l(w_{\mathrm{un}}) + n] \tag{9.101}$$

in the minimal degree ${}^\circ r$ it is of rank 2 or 1 depending on the parity of n.

9.6.2 The lowest K_∞ type in $\mathbb{D}_\lambda$

The maximal compact subgroup K_∞ is the fixed group of the standard Cartan-involution $\Theta : g \mapsto {}^t g^{-1}$. The subgroup ${}^\circ M$ is fixed under Θ and the subgroup $\mathrm{SO}(2)\times\mathrm{SO}(2)\times\cdots\times\mathrm{SO}(2) = K_\infty^{{}^\circ M,(1)} = T_1^c$ is a maximal torus in K_∞. It is the stabilizer of a direct sum decompositions of $\mathbb{R}^n$ into two dimensional oriented planes V_i plus a line $\mathbb{R}z$ if n is odd, we write

$$\mathbb{R}^n = \bigoplus V_i \oplus (\mathbb{R}z) \tag{9.102}$$

The Cartan involution is the identity on our torus $T_1^c/\mathbb{R}$. This torus can be supplemented to a $\Theta-$ stable maximal torus by multiplying it by the torus $T_{1,\mathrm{split}}$ which is the product of the diagonal tori acting on the V_i in (9.102) times another copy of $\mathbb{G}_m$ acting on $\mathbb{R}z$ (if necessary). So we get a maximal torus $T_1 = T_1^c \cdot T_{1,\mathrm{split}}$. Obviously T_1 is the centralizer of T_1^c and the centralizer of $T_{1,\mathrm{split}}$ is the group ${}^\circ M$.

If we base change to $\mathbb{C}$ then T_1^c splits. We identify

$$\mathrm{SO}(2) \xrightarrow{\sim} \begin{pmatrix} a & b \\ -b & a \end{pmatrix} \tag{9.103}$$

and then the character group $X^*(T_1^c \times \mathbb{C}) = \oplus \mathbb{Z}e_\nu$ where on the ν-th component $e_\nu : \begin{pmatrix} a & b \\ -b & a \end{pmatrix} \mapsto a + bi = a + b\sqrt{-1}$. Then this choice provides a Borel subgroup $B_c \supset T_1^c \times \mathbb{C}$, for which the simple roots $\alpha_1^c, \alpha_2^c, \ldots, \alpha_{{}^\circ r}^c$ are

$$\begin{cases} e_1 - e_2, e_2 - e_3, \ldots, e_{{}^\circ r-1} - e_{{}^\circ r}, e_{{}^\circ r-1} + e_{{}^\circ r} & \text{for } n \text{ even} \\ e_1 - e_2, e_2 - e_3, \ldots, e_{{}^\circ r} & \text{if } n \text{ is odd} \end{cases}$$

(See [Bou]). For n even we get the fundamental dominant weights

$$\gamma_\nu^c = \begin{cases} e_1 + e_2 + \cdots + e_\nu, & \text{if } \nu <^\circ r - 1 \\ \frac{1}{2}(e_1 + e_2 + \cdots + e_{{}^\circ r-1} - e_{{}^\circ r}) & \text{if } \nu =^\circ r - 1 \\ \frac{1}{2}(e_1 + e_2 + \cdots + e_{{}^\circ r-1} + e_{{}^\circ r}) & \text{if } \nu =^\circ r \end{cases} \tag{9.104}$$

and for n odd we get

$$\gamma_\nu^c = \begin{cases} e_1 + e_2 + \cdots + e_\nu, & \text{if } \nu <^\circ r \\ \frac{1}{2}(e_1 + e_2 + \cdots + e_{{}^\circ r}) & \text{last weight} \end{cases} \tag{9.105}$$

An easy calculation shows

$$\sum_{i=1}^{{}^\circ r} g_i e_i = \begin{cases} (g_1 - g_2)\gamma_1^c + (g_2 - g_3)\gamma_2^c + \cdots + (g_{{}^\circ r-1} - g_{{}^\circ r})\gamma_{{}^\circ r-1}^c + (g_{{}^\circ r-1} + g_{{}^\circ r})\gamma_{{}^\circ r}^c & n \text{ even} \\ (g_1 - g_2)\gamma_1^c + (g_2 - g_3)\gamma_2^c + \cdots + (g_{{}^\circ r-1} - g_{{}^\circ r})\gamma_{{}^\circ r-1} + 2g_{{}^\circ r}\gamma_{{}^\circ r}^c & n \text{ odd} \end{cases} \tag{9.106}$$

The character $\sum_{i=1}^{{}^\circ r} g_i e_i$ is dominant (with respect to B_c) if

$$\begin{cases} g_1 \geq g_2 \geq \ldots g_{{}^\circ r-1} \geq \pm g_{{}^\circ r} & \text{if } n \text{ is even} \\ g_1 \geq g_2 \geq \cdots \geq g_{{}^\circ r-1} \geq g_{{}^\circ r} \geq 0 \end{cases} \tag{9.107}$$

Under the action of $K_\infty^{(1)}$ the $(\mathfrak{g}, K_\infty^{(1)})$- module $\mathbb{D}_\lambda$ decomposes into a direct sum

$$\mathbb{D}_\lambda = \bigoplus_{\mu^c} \mathbb{D}_\lambda(\Theta_{\mu^c}) \tag{9.108}$$

where $\mu^c \in X^*(T^c \times \mathbb{C})$ is a highest weight, Θ_{μ^c} is the resulting irreducible K_∞-module and $\mathbb{D}_\lambda(\Theta_{\mu^c})$ is the isotypical component.

We introduce the highest weight (see (9.81))

$$\mu_0^c(\lambda) = (b_1+2)e_1 + (b_3+2)e_2 + \cdots + (b_{2^\circ r-1}+2)e_{^\circ r} \tag{9.109}$$

and and in terms of our dominant weight λ this is

$$\mu_0^c(\lambda) = \begin{cases} 2(a_1+1)\gamma_1^c + \cdots + 2(a_{^\circ r-1}+1)\gamma_{^\circ r-1}^c + 2(a_{^\circ r-1}+a_{^\circ r}+3)\gamma_{^\circ r}^c & \text{if } n \text{ is even} \\ 2(a_1+1)\gamma_1^c + \cdots + 2(a_{^\circ r}+3)\gamma_{^\circ r}^c & \text{if } n \text{ is odd} \end{cases} \tag{9.110}$$

For $\lambda = 0$ we get an expression (not depending on the parity of n)

$$\mu_0^c(0) = 2\gamma_1^c + \cdots + 2\gamma_{^\circ r-1}^c + 6\gamma_{^\circ r}^c \tag{9.111}$$

In the case that n is even the group K_∞ contains the element θ which maps $e_i \to e_i$ for $i \leq^\circ r-1$ and $e_{^\circ r} \to -e_{^\circ r}$ or what amounts to the same exchanges $\gamma_{^\circ r-1}^c$ and $\gamma_{^\circ r}^c$ and fixes the other fundamental dominant weights. Then

$$\bar{\mu}_0^c(\lambda) := \vartheta(\mu_0^c(\lambda)) = 2\gamma_1^c + \cdots + 6\gamma_{^\circ r-1}^c + 2\gamma_{^\circ r}^c + \vartheta(\lambda^c) \tag{9.112}$$

Proposition 9.6.1. *If n is odd then the $K_\infty^{(1)}$- type $\Theta_{\mu_0^c(\lambda)}$ occurs in $\mathbb{D}_\lambda$ with multiplicity one. All other occurring $K_\infty^{(1)}$ types are "larger", i.e. their highest weight satisfies $\mu^c = \mu_0^c(\lambda) + \sum n_i\alpha_i^c$ with $n_i \geq 0$. We have*

$$H^\bullet(\mathfrak{g}, K_\infty, \mathbb{D}_\lambda \otimes \mathcal{M}_\lambda) = \mathit{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \Theta_{\mu_0^c(\lambda)} \otimes \mathcal{M}_\lambda)$$

If n is even then the $(\mathfrak{g}, K_\infty^{(1)})$ module $\mathbb{D}_\lambda$ decomposes into two irreducible sub modules

$$\mathbb{D}_\lambda = \mathbb{D}_\lambda^+ \oplus \mathbb{D}_\lambda^-.$$

The $K_\infty^{(1)}$ types $\Theta_{\mu_0^c(\lambda)}$ resp. $\Theta_{\bar{\mu}_0^c(\lambda)}$ occur with multiplicity one (resp. zero) in $\mathbb{D}_\lambda^+$(resp. $\mathbb{D}_\lambda^-$). They are the lowest $K_\infty^{(1)}$ types respectively. We have

$$H^\bullet(\mathfrak{g}, K_\infty^{(1)}, \mathbb{D}_\lambda \otimes \mathcal{M}_\lambda) = H^\bullet(\mathfrak{g}, K_\infty^{(1)}, \mathbb{D}_\lambda^+ \otimes \mathcal{M}_\lambda) \oplus H^\bullet(\mathfrak{g}, K_\infty^{(1)}, \mathbb{D}_\lambda^- \otimes \mathcal{M}_\lambda) =$$

$$\mathit{Hom}_{K_\infty^{(1)}}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \Theta_{\mu_0^c(\lambda)} \otimes \mathcal{M}_\lambda) \oplus \ \mathit{Hom}_{K_\infty^{(1)}}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \Theta_{\bar{\mu}_0^c(\lambda)} \otimes \mathcal{M}_\lambda)$$

Proof. For two fundamental weights we write $\mu^c \geq \mu_1^c$ if μ^c is "larger" than μ_1^c in the above sense. We start from (9.96) and consider a single summand $\mathrm{Ind}_{K_\infty^\circ M^{(1)}}^{K_\infty^{(1)}} \mathbb{C}\psi_{\varepsilon_i(b_i+2+2\nu_i)}$. This induced module decomposes into isotypical modules

$$\mathrm{Ind}_{K_\infty^\circ M^{(1)}}^{K_\infty^{(1)}} \mathbb{C}\psi_{\varepsilon_i(b_i+2+2\nu_i)} = \bigoplus_{\mu^c} \mathrm{Ind}_{K_\infty^\circ M^{(1)}}^{K_\infty^{(1)}} \mathbb{C}\psi_{\varepsilon_i(b_i+2+2\nu_i)}(\Theta_{\mu^c}) \tag{9.113}$$

where μ^c runs over the set of dominant weights, where Θ_{μ^c} is the irreducible module of highest weight μ^c and where $\mathrm{Ind}_{K_\infty^\circ M^{(1)}}^{K_\infty^{(1)}} \mathbb{C}\psi_{\varepsilon_i(b_i+2+2\nu_i)}(\Theta_{\mu^c})$ is the isotypical component. If we pick any dominant weight μ^c then Frobenius reciprocity yields that

$$\begin{gathered}\Theta_{\mu^c} \text{ occurs in } \mathrm{Ind}_{K_\infty^\circ M^{(1)}}^{K_\infty^{(1)}} \mathbb{C}\psi_{\varepsilon_i(b_i+2+2\nu_i)} \text{ with multiplicity } k \iff \\ t \mapsto \prod_j e_i(t)^{\varepsilon_i(b_i+2+2\nu_i)} \text{ occurs in } \Theta_{\mu^c} \text{ with multiplicity } k\end{gathered} \tag{9.114}$$

and if $k > 0$ this implies $\mu^c \geq t \mapsto \prod_j e_i(t)^{\varepsilon_i(b_i+2+2\nu_i)}(t)$. It it easy to see that we get minimal $K_\infty^{(1)}$ types only if all $\nu_i = 0$. But

$$t \mapsto \prod_j e_i(t)^{\varepsilon_i(b_i+2)} \text{ is dominant } \iff \begin{cases} \varepsilon = (1,1,\dots,1,\pm 1) \text{ if } n \text{ even} \\ \varepsilon = (1,1,\dots,1,1) \text{ if } n \text{ odd} \end{cases} \tag{9.115}$$

and in the n even case these two characters are exactly $\mu_0^c(\lambda)$ and $\bar{\mu}_0^c(\lambda)$ and in the n odd case this character is $\mu_0^c(\lambda)$.

□

9.6.3 The unitary modules with cohomology, cohomological induction.

We start from an essentially self dual highest weight λ and the attached highest weight module $\mathcal{M}_\lambda$. In their paper [Vo-Zu] Vogan and Zuckerman construct a finite family of $(\mathfrak{g}, K_\infty)$ modules denoted by $A_\mathfrak{q}(\lambda)$ which have non trivial cohomology with coefficients in $\mathcal{M}_\lambda$., i.e.

$$H^\bullet(\mathfrak{g}, K_\infty, A_\mathfrak{q}(\lambda) \otimes \mathcal{M}_\lambda) \neq 0$$

They also show that all unitary irreducible $(\mathfrak{g}, K_\infty)$ -modules with non trivial cohomology in with coefficients in $\mathcal{M}_\lambda$. are of this form. We briefly recall their construction and translate it into our language and our way of thinking about these issues.

We introduce the torus $\mathbb{S}^1/\mathbb{R}$ whose group of real points is the unit circle in $\mathbb{C}^\times$ and we chose once for all an isomorphism

$$i_0 : \mathbb{S}^1 \times_\mathbb{R} \mathbb{C} \xrightarrow{\sim} \mathbb{G}_m/\mathbb{C} \tag{9.116}$$

We consider the free $\mathbb{Z}$ module

$$\mathrm{Hom}_\mathbb{R}(\mathbb{S}^1, T_1^c) = \mathrm{Hom}_\mathbb{R}(\mathbb{S}^1, T_1) = X_*(T_1^c \times_\mathbb{R} \mathbb{C})$$

where of course the last identification depends on the choice of i_0. We have the standard pairing $< \ , \ > : X_*(T_1 \times_\mathbb{R} \mathbb{C}) \times X^*(T_1 \times_\mathbb{R} \mathbb{C}) \to \mathbb{Z}$.

The first ingredient in the construction of an $A_\mathfrak{q}(\lambda)$ is the choice of a cocharacter $\chi : \mathbb{S}^1 \to T_c$ (defined over $\mathbb{R}$). From this cocharacter we get the centralizer Z_χ , this is a reductive subgroup whose set of roots is

$$\Delta_\chi = \{\alpha \in \Delta \subset X^*(T_1 \times_\mathbb{R} \mathbb{C}) | \ < \chi, \alpha >= 0\}.$$

We can also define

$$\Delta_\chi^+ = \{\alpha | < \chi, \alpha >> 0\},$$

this set depends on the choice of i_0 (see (9.116)). This provides a parabolic subgroup $P_\chi \subset G \times_{\mathbb{R}} \mathbb{C}$ whose system of roots is $\Delta_\chi \cup \Delta_\chi^+$. Clearly $\Theta(P_\chi) = P_\chi$ hence P_χ is the Θ-stable parabolic subgroup attached to the datum χ. This parabolic subgroup is only defined over $\mathbb{C}$, if we intersect it with its conjugate $\bar{P}_\chi$ then we get the centralizer Z_χ of χ. We relate this to the notations in [Vo-Zu]: the $\mathfrak{q}$ in $A_\mathfrak{q}(\lambda)$ is the Lie-algebra of P_χ, the group Z_χ is the L. Let $\mathfrak{u}_\chi$ be the Lie algebra of U_χ. The datum χ determines the $\mathfrak{q}$ in $A_\mathfrak{q}(\lambda)$. We could introduce the notation $A_\mathfrak{q}(\lambda) = A_\chi(\lambda)$. Since T_1 is the centralizer of T_c we can find a generic cocharacter χ_{gen} such that $P_{\chi_{\text{gen}}} = B_c$ our chosen Borel subgroup in ${}^\circ M$.

To a highest weight λ which is trivial on the semi-simple part $Z_\chi^{(1)}$ Vogan-Zuckerman attach an irreducible unitary $(\mathfrak{g}, K_\infty)$ module $A_\mathfrak{q}(\lambda)$ such that

$$H^\bullet(\mathfrak{g}, K_\infty, A_\mathfrak{q}(\lambda) \otimes \mathcal{M}_\lambda) \neq 0.$$

Vogan and Zuckerman show (based on results of many others) that all the unitary irreducible $(\mathfrak{g}, K_\infty)$ modules with non trivial cohomology in $\mathcal{M}_\lambda$ are isomorphic to an $A_\mathfrak{q}(\lambda)$.

Furthermore they give a description of the K_∞ types occurring in $A_\mathfrak{q}(\lambda)$ especially they show that $A_\mathfrak{q}(\lambda)$ contains a lowest K_∞ type. This lowest K_∞-type is given by a dominant weight which obtained by the following rule:

We consider the action of the group K_∞ on the unipotent radical U_χ and on the Lie algebra $\mathfrak{u}_\chi$ and the restriction of this action to T_1^c. The torus T_1 also acts on $\mathfrak{u}_\chi$ and under this action we get a decomposition into one dimensional eigenspaces

$$\mathfrak{u}_\chi = \bigoplus_{\alpha \in \Delta_\chi^+} \mathfrak{u}_\alpha$$

let us choose generators X_α in these eigenspaces. We observe that the roots $\alpha, \Theta\alpha \in \Delta^+$ induce the same root α_c on T_1^c. The vector $V_{\alpha_c} = X_\alpha - \Theta X_\alpha \in \mathfrak{u}_\chi$ is a non zero eigenvector for T_1^c and

$$\mathfrak{u}_\chi \cap (\mathfrak{p} \otimes \mathbb{C}) = \bigoplus_{(\alpha, \Theta\alpha) \in \Delta_\chi^+} \mathbb{C} V_{\alpha_c}$$

the sum runs over the unordered pairs. Then

$$\mu_c(\chi, \lambda) = \sum_{(\alpha, \Theta\alpha) \in \Delta_\chi^+} \alpha_c + \lambda_c \tag{9.117}$$

is a highest weight of a representation $\Theta_{\mu_c(\chi,\lambda)}$ of $K_\infty^{(1)}$ and this is the lowest $K_\infty^{(1)}$ type in $A_\mathfrak{q}(\lambda)$. We get

$$H^\bullet(\mathfrak{g}, K_\infty^{(1)}, A_\mathfrak{q}(\lambda) \otimes \mathcal{M}_\lambda) = \mathrm{Hom}_{K_\infty^{(1)}}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), A_\mathfrak{q}(\lambda) \otimes \mathcal{M}_\lambda) = \mathrm{Hom}_{K_\infty^{(1)}}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \Theta_{\mu_c(\chi,\lambda)} \otimes \mathcal{M}_\lambda) \tag{9.118}$$

The module is determined by these properties:

1) It has non trivial cohomology with coefficients in $\mathcal{M}_\lambda$

2) It has $\mu_c(\chi,\lambda)$ as highest weight of a minimal K_∞ type. (See Thm. 5. 3 in [Vo-Zu].)

Recall that our aim at this moment is to identify the module J_{σ_∞} to an $A_{\mathfrak{q}}(\lambda)$, and to achieve this goal we exhibit a list of very specific $A_{\mathfrak{q}}(\lambda)$'s.

Comparison of two tori

We need to compute $\mu_c(\chi,\lambda)$ and to achieve this goal the author of this book modifies the Cartan involution in order to do the computation in a split group. Our standard torus T is contained in the standard Borel subgroup B of upper triangular matrices. Let w_0 be an element in the normalizer of T which conjugates B into its opposite Borel subgroup. If we replace our Cartan involution by $\Theta_1 = w_0\Theta$ then Θ_1 fixes T and the Borel subgroup B. This is not a Cartan involution, but it is easily seen that it is conjugate to Θ over $\mathrm{Gl}_n(\mathbb{C})$. and

$$\Theta_1 : \begin{pmatrix} t_1 & 0 & 0 & \dots & \\ 0 & t_2 & \dots & \dots & \\ 0 & 0 & \ddots & 0 & \dots \\ 0 & & \dots & t_{n-1} & \\ 0 & & & & t_n \end{pmatrix} \mapsto \begin{pmatrix} t_n^{-1} & 0 & 0 & \dots & \\ 0 & t_{n-1}^{-1} & \dots & \dots & \\ 0 & 0 & \ddots & 0 & \dots \\ 0 & & \dots & t_2^{-1} & \\ 0 & & & & t_1^{-1} \end{pmatrix} \tag{9.119}$$

We can decompose T up to isogeny into a torus T_c on which Θ_1 acts by the identity and a torus T_{split} where it acts by $x \mapsto x^{-1}$:

$$T_c = \{ \begin{pmatrix} t_1 & 0 & 0 & \dots & \\ 0 & t_2 & \dots & \dots & \\ 0 & 0 & \ddots & 0 & \dots \\ 0 & & \dots & t_2^{-1} & \\ 0 & & & & t_1^{-1} \end{pmatrix} \} \text{ resp. } T_{\mathrm{split}} = \{ \begin{pmatrix} t_1 & 0 & 0 & \dots & \\ 0 & t_2 & \dots & \dots & \\ 0 & 0 & \ddots & 0 & \dots \\ 0 & & \dots & t_2 & \\ 0 & & & & t_1 \end{pmatrix} \}$$

It is clear that a suitable permutation matrix conjugates $T_{1,\mathrm{split}}$ into T_{split}. This permutation matrix maps the centralizer of $T_{1,\mathrm{split}}$ (which is ${}^\circ M$) to the centralizer ${}^\circ M'$ of T_{split} and the anisotropic torus T_1^c to an anisotropic torus $T_1^{c\prime}$ in ${}^\circ M'$. Then we can find an element $m \in {}^\circ M'(\mathbb{C})$ which conjugates $T_1^{c\prime} \times \mathbb{C}$ into T_c.

The composition of these conjugations provides an identification of the character modules $X^*(T_1 \times \mathbb{C}) = X^*(T)$ which respects the product decompositions and hence we get

$$X^*(T_1^c \times \mathbb{C}) = X^*(T_c). \tag{9.120}$$

We choose our conjugating element m such that the $e_i \in X^*(T_1^c \times \mathbb{C})$ are mapped to the element $t \mapsto t_i$ (for $i = 1$ to ${}^\circ r$).

Inside $X^*(T)$ we have the dominant fundamental weights $\gamma_1, \dots, \gamma_{n-1}$, let $\bar\gamma_i$ be the restriction of γ_i to T_1^c then we have $\bar\gamma_i = \bar\gamma_{n-i}$. We can interpret the

$\bar\gamma_i$ also as elements in $X^*(T_1\times\mathbb{C})\otimes\mathbb{Q}$ we require that the restriction of $\bar\gamma_i$ to $T_{1,\mathrm{split}}$ is trivial. Then we can write

$$\bar\gamma_i=\begin{cases}\frac{1}{2}(\gamma_i+\gamma_{n-i}) & \text{if } i\neq\frac{n}{2}\\ \gamma_i & \text{else}\end{cases}\tag{9.121}$$

We can relate the dominant weights γ_i^c and the $\bar\gamma_i$: If n is even then

$$\gamma_\nu^c=\bar\gamma_\nu \text{ for } 1\le\nu<^\circ r-1,\ \gamma^c_{\circ r-1}=\bar\gamma_{\circ r-1}-\frac{1}{2}\bar\gamma_{\circ r},\ \gamma^c_{\circ r}=\frac{1}{2}\bar\gamma_{\circ r}\tag{9.122}$$

For n odd we get

$$\gamma_\nu^c=\bar\gamma_\nu \text{ for } 1\le\nu<^\circ r,\ \gamma^c_{\circ r}=\frac{1}{2}\bar\gamma_{\circ r}$$

The Borel subgroup B is invariant under Θ_1, the root subgroup $U_{i,j}; 1\le i< l\le n$ is conjugated into $U_{n+1-j,n+1-i}$. Inside the unipotent radical we have the half diagonal of spots $(^\circ r,{}^\circ r+1+2\epsilon(n)),\dots(2,n-1),(1,n)$ The involution is a reflection along this half diagonal and the spots on the left of the half diagonal form a system of representatives for $\sim\Theta_1$. Of course we have a corresponding Borel subgroup $B_1\supset T_1\times\mathbb{C}$ of $G\times\mathbb{C}$.

Proposition 9.6.2. *Under the above identification the restrictions of the* $\overset{\circ}{\gamma}{}^M_{2i-1}$ *to* T_c *are equal to the* e_i *in* $X^*(T_1^c\times\mathbb{C})$.

We want to compute $\mu_c(\chi,\lambda)$. By definition this is an element in $X^*(T_c\times\mathbb{C})$ using the identification in (9.6.3) we carry out this computation in $X^*(T_c)$. A cocharacter $\chi:\mathbb{G}_m\to T_c$ is of the form

$$\chi: t\mapsto\begin{pmatrix}t^{m_1} & 0 & 0 & \dots & \\ 0 & t^{m_2} & \dots & \dots & \\ 0 & 0 & \ddots & 0 & \dots\\ 0 & & \dots & t^{-m_2} & \\ 0 & & & & t^{-m_1}\end{pmatrix}$$

since we want $P_\chi\supset B_1$ we require $m_1\ge m_2\ge m_{\circ r}\ge 0$. (If n is odd then there is an $m_{\circ r+1}=0$). Let us start with the regular case, this means that all $\ge$ signs are actually strict, i.e. $>$ signs. Then it an easy computation that

$$\mu_c(\chi_{\mathrm{reg}},\lambda)=\begin{cases}ne_1+(n-2)e_2+\dots+2e_{\circ r}+\lambda_c & \text{if } n \text{ is even}\\ ne_1+(n-2)e_2+\dots+3e_{\circ r}+\lambda_c & \text{if } n \text{ is odd}\end{cases}\tag{9.123}$$

The set $\Delta^+_{\chi_{\mathrm{reg}}}$ is the set of roots of B modulo the conjugation Θ_1. Hence we see that

$$\mu_c(\chi_{\mathrm{reg}},\lambda)=\mu_0^c(\lambda).$$

The interesting contribution is in fact $\mu_c(\chi_{\mathrm{reg}},,0)$ and this is the number μ_0^c in (9.111) We can express $\mu_c(\chi_{\mathrm{reg}},0)$ in terms of the fundamental weights γ_i (or the $\bar\gamma_i$) we use the formulas (9.122). We get

$$\mu_c(\chi_{\mathrm{reg}},0)=2\bar\gamma_1+2\bar\gamma_2+\dots+2\bar\gamma_{\circ r-1}+\begin{cases}2\bar\gamma_{\circ r} & n\equiv 0 \mod 2\\ 6\bar\gamma_{\circ r} & n\equiv 1\mod 2\end{cases}\tag{9.124}$$

If χ is not regular then the relevant information extracted from χ is the list

$$t_\chi = (t_1, t_2, \dots, t_s; t_0)$$

(the type of χ) where the t_i are the length of the intervals where the $m_i > 0$ are constant, i.e. $m_1 = m_2 = \dots = m_{t_1} > m_{t_1+1} = \dots = m_{t_1+t_2} > \dots$. The number t_0 is the length of the interval where $m_i = 0$. The Θ stable parabolic P_χ subgroup only depends on t_χ. The types t_χ have to satisfy the (only) constraint

$$2\sum t_\nu + t_0 = n \tag{9.125}$$

The regular case corresponds to the list $(1, 1, \dots, 1; 0 \text{ or } 1)$. In the general case we get a decorated Dynkin diagram where the crossed out roots are those where the m_i jump.

$$-\times-\circ-\circ-\circ-\times-\times-\circ-\cdots-\circ-\times\cdots\times-\circ-\cdots-\circ$$

This decorated diagram is symmetric under the reflection $i \mapsto n-i$. We look at the connected component of $\circ$-s. These components come in pairs unless the component is invariant under the reflection, i.e. it is central. The non central pairs

$$\pi_{\chi,\nu} = \begin{matrix} \times- & \circ- & \cdots- & \circ & -\times-\cdots\times- & \circ & -\cdots- & \circ \\ & \alpha_{i_\nu} & & \alpha_{j_\nu} & & \alpha_{n-j_\nu} & & \alpha_{n-i_\nu} \end{matrix} \tag{9.126}$$

are labelled by the indices ν for which $t_\nu > 1$, and are of length $t_\nu - 1 = j_\nu - i_\nu + 1$. (The meaning of the indices i_ν, j_ν is explained in the diagram). The central connected component is of length $t_0 - 1$, of course it may be empty. We write it as

$$\pi_{\chi,0} = \begin{matrix} \times- & \circ & -\cdots- & \circ & -\times \\ & \alpha_{i_0} & & \alpha_{j_0} & \end{matrix} \tag{9.127}$$

where of course $i_0 = n - j_0$. Let π_χ be the union of these connected components. Let Δ^+_ν be the set of positive roots which are sums of roots in π_ν.

To compute $\mu_c(\chi, 0)$ we have to subtract from $\mu_c(\chi_{\text{reg}}, 0)$ the sum of roots in Δ^+_ν with $j_\nu <^\circ r$ and the sum of roots in $\Delta^+_0/\{\Theta_1\}$.

A simple calculation shows that for $\nu > 0$

$$2\rho^{(\nu)} = \sum_{i=i_\nu}^{i=j_\nu} \gamma_i + \gamma_{n-i} - (t_\nu - 1)(\gamma_{i_\nu - 1} + \gamma_{i_\mu + 1}) \tag{9.128}$$

where we put $\gamma_{-1} = \gamma_n = 0$. This means that subtracting $2\rho^{(\nu)}$ from the sum which yields $\mu_c(\chi_{\text{reg}}, 0)$ has the effect that the sum $\sum_{i=i_\nu}^{i=j_\nu} \gamma_i + \gamma_{n-i} = 2\sum \bar{\gamma}_i$ cancels out and we have to add $(t_\nu - 1)(\gamma_{i_\nu - 1} + \gamma_{i_\mu + 1})$. Observe that $i_{\nu-1}, j_{\mu+1} \notin \pi_\chi$. We still have to subtract the contribution from the central component Δ^+_0. We have to sum the roots in $\Delta^+_0/\{\Theta_1\}$ this means that we take half the sum of all roots and add half the sum of the symmetric roots. This yields

$$2\rho^{(0)} = \frac{1}{2}((j_0 - i_0 + 1)\alpha_{i_0} + \dots + (j_0 - i_0 + 1)\alpha_{j_0}) + \frac{1}{2}(\alpha_{i_0} + \dots + \dots + \alpha_{j_0}) =$$

$$((j_0 - i_0 + 2)\bar{\alpha}_{i_0} + \cdots + (\ldots)\bar{\alpha}_{\circ r}$$

we see again that the sum $\sum_{i=i_0}^{n-i_0} \bar{\gamma}_i$ drops out and we have to add a term $t_0(\gamma_{i_0-1} + \gamma_{i_0+1})$.

Hence we get: Let π_χ^c be the union of the π_ν^c and π_0^c. Then

$$\mu_c(\chi, 0) = \sum_{i \notin \pi_\chi^c} (2 + c_i(\chi, 0))\gamma_i^c$$

where

$$c_i(\chi, 0) = \begin{cases} (t_{\nu^-} - 1) + (t_{\nu^+} - 1) & \text{if } \nu \neq 0 \\ (t_{\nu^-} - 1) + t_{\nu^+} & \text{if } \nu = 0 \end{cases} \tag{9.129}$$

and where $t_{\nu^-} - 1$ is the length of connected component directly to the left of $i_\nu - 1$ and $t_{\nu^+} - 1$ is the length of the component directly to the right of $i_\nu - 1$.

If we have chosen a highest weight $\lambda = \sum a_i \gamma_i$ then we require $a_i = a_{n+1-i} \geq 0$ and we must have $a_i = 0$ for all $i \in \pi_\chi$. Then

$$\mu_c(\chi, \lambda) = \sum_{i \notin \pi_\chi} (2 + c_i(\chi, 0) + 2a_i)\gamma_i^c.$$

For us a special case is of interest. We decompose $n = uv$ and take $\chi_{u,v} = \chi$ of type $t_\chi = (v, v, \ldots, v)$. Hence the reductive quotient of the Θ stable parabolic subgroup is $M^\vee = \mathrm{Gl}_v \times \mathrm{Gl}_v \times \cdots \times \mathrm{Gl}_v$, the number of factors is u. In this case we get

$$\begin{array}{ccccccccccccc} \circ & - & \circ & \cdots - & \circ - & \times & - \circ - & \circ - \cdots - & \circ - \times & - \circ \ldots \\ \alpha_1 & & \alpha_2 & & \alpha_{v-1} & \alpha_v & \alpha_{v+1} & & \alpha_{2v-1}\ \alpha_{2v} & \end{array} \tag{9.130}$$

so the indices outside π_χ are the multiples of v. Let us denote by $\mathfrak{q}$ the Lie-algebra of $P_{\chi_{u,v}}$.

$$\mu_c(\chi_{u,v}, \lambda) = \sum_{\nu : \nu v \leq \frac{u}{2}} (2 + 2(v-1) + e(\nu))\gamma_{\nu v}^c + \lambda_c \tag{9.131}$$

where $e(\nu) = 0$ except in the case that $^\circ r \in [\nu v, (\nu+1)v]$ and then it is equal to 1.

9.6.4 The $A_{\mathfrak{q}_{u,v}}(\lambda)$ as Langlands quotients

Let $n = uv$ and $\mathfrak{q} = \mathfrak{q}_{u,v}$ as above. The parabolic is $P_{\chi_{u,v}}$ To realize $A_{\mathfrak{q}_{u,v}}(\lambda)$ as Langlands quotient we apply the procedure described in [Vo-Zu], p.82-83. We have to find a parabolic subgroup $P \subset \mathrm{Gl}_n/\mathbb{R}$ and a tempered representation σ_∞ of $M = P/U$ such that

a) our λ is a character on P,

b) the module ${}^{\mathrm{a}}\mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})}\sigma_\infty$ has the right infinitesimal character,

c) the module $\mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})}\sigma_\infty$ restricted to K_∞ contains $\mu_c(\chi_{u,v},\lambda_c)$ as minimal K_∞ type.

To get our parabolic subgroup we choose a cocharater $\eta_{u,v}:\mathbb{G}_m\to T$, this cocharacter is defined as

$$t\mapsto\eta_{u,v}(t)=\begin{pmatrix} t^v & 0 & 0 & & & \dots & \\ 0 & t^{v-1} & \dots & \dots & & & \\ 0 & 0 & \ddots & 0 & \dots & & \\ 0 & & \dots & t^1 & & & \\ 0 & & & & t^v & & \\ 0 & & & & & t^{v-1} & \\ 0 & & & & & & \ddots \end{pmatrix} \tag{9.132}$$

i.e. we have u copies of the diagonal matrix $\mathrm{diag}(t^v,t^{v-1},\dots,t)$ on the diagonal.

This cocharacter $\eta=\eta_{u,v}(t)$ yields a parabolic subgroup P_η which contains the torus and has as roots $\Delta_\eta=\{\alpha|<\eta,\alpha>\geq 0\}$. Its reductive quotient is $\mathrm{Gl}_u\times\mathrm{Gl}_u\times\dots\times\mathrm{Gl}_u$ where the number of factors is v. The embedding into Gl_n is not the obvious one and P_η does not contain the standard Borel subgroup of upper triangular matrices.

To describe the relation between these two groups we denote by $\mathfrak{e}_1,\mathfrak{e}_2,\dots,\mathfrak{e}_n$ the standard orthonormal basis of our underlying vector space $\mathbb{R}^n$. Then we group these basis elements

$$\{\{\mathfrak{e}_1,\dots,\mathfrak{e}_v\},\{\{\mathfrak{e}_{v+1},\dots,\mathfrak{e}_{2v}\},\dots,\{\mathfrak{e}_{(u-1)v+1},\dots,\mathfrak{e}_{uv}\}\}$$

and this grouping yields a direct sum decomposition

$$\mathbb{R}^n=(\mathbb{R}\mathfrak{e}_1\oplus\dots\oplus\mathbb{R}\mathfrak{e}_v)\oplus(\mathbb{R}\mathfrak{e}_{v+1}\oplus\dots\oplus\mathbb{R}\mathfrak{e}_{2v})\oplus\dots\oplus(\mathbb{R}\mathfrak{e}_{(u-1)v+1},\dots,\mathbb{R}\mathfrak{e}_{uv})=$$
$$V_1\oplus V_2\oplus\dots\oplus V_u \tag{9.133}$$

and then $M^\vee=\mathrm{Gl}(V_1)\times\dots\times\mathrm{Gl}(V_u)$.

We get a second grouping of the basis elements

$$\{\{\mathfrak{e}_1,\mathfrak{e}_{v+1},\dots,\mathfrak{e}_{(u-1)v+1}\},\{\mathfrak{e}_2,\mathfrak{e}_{v+2},\dots,\mathfrak{e}_{(u-1)v+2}\},\dots\},\{\dots\mathfrak{e}_{uv}\}\} \tag{9.134}$$

which yields direct sum decomposition

$$\mathbb{R}^n=\left(\mathbb{R}\mathfrak{e}_1\oplus\mathbb{R}\mathfrak{e}_{v+1}\oplus\dots\oplus\mathbb{R}\mathfrak{e}_{(u-1)v+1}\right)\oplus\left(\mathbb{R}\mathfrak{e}_2\oplus\mathbb{R}\mathfrak{e}_{v+2}\oplus\dots\oplus\mathbb{R}\mathfrak{e}_{(u-1)v+2}\right)\oplus\dots$$
$$W_1\oplus W_2\oplus\dots\oplus W_v \tag{9.135}$$

and then $M=\mathrm{Gl}(W_1)\times\mathrm{Gl}(W_2)\times\dots\times\ \mathrm{Gl}(W_v)=\mathrm{Gl}_u\times\mathrm{Gl}_u\times\dots\times\mathrm{Gl}_u$. The groups $M^\vee$ and M are mutual centralizers of each other.

The two groupings define two different Borel subgroups, the first one defines the standard Borel B of upper triangular matrices and the second Borel B^* fixes the flag $\{\mathfrak{e}_1\},\{\mathfrak{e}_1,\mathfrak{e}_{v+1}\}\dots$. Let us denote by $\lambda^*,\rho^*,w^*_{u,v},\dots$ the dominant weight with respect to B^*, the half sum of positive roots and so on. Our highest weight λ is trivial on the semi simple part of $M^\vee$ it must be of the form (9.70) Now we consider the highest weight for the group M

$$\begin{aligned} w^*_{u,v}(\lambda^*+\rho^*)-\rho^* = \underline{\mu}* = (a_1+v-1)(\gamma_1^{*,M}+\gamma_{1+u}^{*,M}+\cdots+\gamma_{1+(v-1)u}^{*,M})+ \\ (a_2+v-1)(\gamma_2^{*,M}+\gamma_{2+u}^{*,M}+\cdots+\gamma_{2+(v-1)u}^{*,M})+ \\ \vdots \\ (a_{u-1}+v-1)(\gamma_{u-1}^{*,M}+\gamma_{u-1+u}^{*,M}+\cdots+\gamma_{u-1+(v-1)u}^{*,M})+ \\ -(u+1)(\gamma_u^*+\gamma_{2u}^*+\cdots+\gamma_{(v-1)u}^*)+d\delta. \end{aligned} \tag{9.136}$$

We choose $\sigma_\infty = \mathbb{D}_{\underline{\mu}^*}$. (See (9.66))

We check the lowest K_∞ type in $\mathrm{Ind}_{P^*}^G \mathbb{D}_{\underline{\mu}^*}$. To compute this lowest K_∞ type we write $M = \prod M_\nu$ where of course each $M_\nu = \mathrm{Gl}_u$. Accordingly we write $T = \prod T_\nu$. The weight $\underline{\mu}^* = \sum \mu_\nu^*$ where the semi simple part is "always the same". We apply the considerations in section 9.6.1 to the factors M_ν. We take $\nu = 1$ then

$$\mu_1^* = (a_1+v-1)\gamma_1^* + (a_2+v-1)\gamma_1^* + \cdots + (a_{u-1}+v-1)\gamma_{u-1}^* + d^*\det{}_u$$

Inside M_1 we have the subgroup ${}^\circ M_1$ which is the reductive Levi factor of ${}^\circ P_1$ as in section 9.6.1 and we have the Kostant element $w_{1,\mathrm{un}}$. Then we consider the character

$$\tilde{\mu}_1^* = w_{1,\mathrm{un}}(\mu_1^*+\rho_1^*)-\rho_1^* = \sum_{i:i \text{ odd}} b_i^* \gamma_i^{{}^\circ M_1^{(1)}} + \tilde{\mu}_1^{*,\mathrm{ab}} \tag{9.137}$$

where again the b_i^* are the cuspidal parameters and they are given by

$$b^*_{2j-1} = v(u+1-2j)-1+\begin{cases} 2a_j+2a_{j+1}+\cdots+2a_{\frac{u}{2}-1}+a_{\frac{u}{2}} & \text{if } u \text{ is even} \\ 2a_j+2a_{j+1}+\cdots+2a_{\frac{u-1}{2}} & \text{if } u \text{ is odd} \end{cases} \tag{9.138}$$

The abelian part $\tilde{\mu}_1^{*,\mathrm{ab}}$ does not play any role in the following (The λ in section (9.6.1) is now μ_1^* and the $\underline{\mu}$ in formula (9.89) is now $\tilde{\mu}_1^*$) We renumber our basis (9.134)

$$\{\mathfrak{f}_1, \mathfrak{f}_2, \ldots, \mathfrak{f}_{u-1}, \mathfrak{f}_u, \ldots\} = \{\mathfrak{e}_1, \mathfrak{e}_{v+1}, \ldots, \mathfrak{e}_{(u-1)v+1}, \mathfrak{e}_2, \ldots\} \tag{9.139}$$

and decompose the space $\mathbb{R}^n$ into a direct sum of euclidian planes (plus a line if n is odd)

$$\mathbb{R}^n = (\mathbb{R}\mathfrak{f}_1 \oplus \mathbb{R}\mathfrak{f}_2) \oplus (\mathbb{R}\mathfrak{f}_3 \oplus \mathbb{R}\mathfrak{f}_4) \oplus \cdots \oplus (\mathbb{R}\mathfrak{f}_n).$$

and this provides a maximal anisotropic torus

$$T_c^* = \mathrm{SO}(2) \times \mathrm{SO}(2) \times \cdots \times \mathrm{SO}(2)$$

In analogy with section 9.6.2 we write

$$X^*(T_c^* \otimes \mathbb{C}) = \oplus \mathbb{Z} f_j \tag{9.140}$$

where f_j is defined in analogy with the e_ν in section 9.6.2.

We have

$$M = \mathrm{Gl}(\mathbb{R}\mathfrak{f}_1 \oplus \mathbb{R}\mathfrak{f}_2 \oplus \cdots \oplus \mathbb{R}\mathfrak{f}_u) \times \cdots \times \mathrm{Gl}(\mathbb{R}\mathfrak{f}_{(v-1)u+1} \oplus \cdots \oplus \mathbb{R}\mathfrak{f}_{uv})$$

and the intersection $T_c^{*,M} = T_c^* \cap M$ is a maximal anisotropic torus in M. It is equal to T_c^* if u is even. If u is odd (and $v > 1$) then it is a proper sub torus, if ${}^\circ r_u = \frac{u-1}{2}$ then

$$T_c^{*,M} = \underbrace{\mathrm{SO}(2) \times \cdots \times \mathrm{SO}(2)}_{{}^\circ r_u \text{ factors}} \qquad \underbrace{\times\{\pm 1\}\times}_{\text{spot } u \text{ and } u+1} \qquad \underbrace{\mathrm{SO}(2) \times \cdots \times \mathrm{SO}(2)}_{{}^\circ r_u \text{ factors}} \times\{\pm 1\}\times \tag{9.141}$$

where the product of signs is one. To get the torus T_c^* we have to put another SO(2) at the spots $(u, u+1), (2u, 2u+1), \ldots$. We apply the reasoning of section (9.6.2) to the factors M_ν.

The representation $\mathbb{D}_{\mu_1^*} = \mathrm{Ind}_{{}^\circ P_\nu}^{M_1} \mathcal{D}_{\tilde{\mu}_1^*}$ contains as lowest $K_\infty^{M_\nu}$ type the representation with highest weight

$$(b_1^* + 2)f_1 + (b_3^* + 2)f_2 + \cdots + (b_{2{}^\circ r_u - 1}^* + 2)f_{{}^\circ r_u}$$

where the b_{2j-1}^* are taken from (9.138). This weight occurs in $\mathcal{D}_{\tilde{\mu}_1^*}$ Hence we see that as a T_c^* module the representation $\otimes\mathcal{D}_{\underline{\tilde{\mu}}_\nu^*}$ contains the weight (depending on u even or odd)

$$\begin{cases} \big((b_1^* + 2)f_1 + (b_3^* + 2)f_2 + \cdots + (b_{2{}^\circ r_u - 1}^* + 2)f_{{}^\circ r_u}\big) + \big((b_1^* + 2)f_{{}^\circ r_u + 1} + \ldots\big) + \ldots \\ \big((b_1^* + 2)f_1 + (b_3^* + 2)f_2 + \cdots + (b_{2{}^\circ r_u - 1}^* + 2)f_{{}^\circ r_u - 1}\big) + \big((b_1^* + 2)f_{{}^\circ r_u + 1} + \ldots\big) + \ldots \end{cases} \tag{9.142}$$

This weight is not dominant, to get a dominant weight we have to reorder the f_ν according to the size of the coefficient in front. Then we get a dominant weight

$$(b_1^* + 2)(f_1^\dagger + f_2^\dagger + \cdots + f_v^\dagger) + (b_3^* + 2)(f_{v+1}^\dagger + f_{v+2}^\dagger + \cdots + f_{2v}^\dagger) + \ldots \tag{9.143}$$

and then formula (9.123) and the formula for the b_j^* give us the following dominant weight expressed in terms of the fundamental dominant weights

$$\sum_{\nu:\nu v \leq \frac{u}{2}} (2v + e(\nu) + 2a_\nu)\gamma_{\nu v}^c \tag{9.144}$$

This is now the weight $\mu_c(\chi_{u,v}, \lambda)$ in (9.123). Hence we see that $\Theta_{\mu_c(\chi_{u,v},\lambda)}$ occurs with multiplicity one in $\mathbb{D}_{\underline{\mu}})$: $\mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_{\underline{\mu}}$ and we get

Theorem 9.6.1. *We have a nonzero intertwining operator* : $T^{(\mathrm{loc})}(\mathbb{D}_{\underline{\mu}})$: $Ind_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_{\underline{\mu}} \to Ind_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_{\underline{\mu}'}$ *and get a diagram*

$$\begin{array}{ccc} Ind_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_{\underline{\mu}} & \xrightarrow{T^{(\mathrm{loc})}(D_\mu)} & A_{\mathfrak{q}}(\lambda) \\ & & \downarrow \\ & & Ind_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_{\mu'} \end{array} \tag{9.145}$$

The horizontal arrow is surjective, and the vertical arrow is injective. The map induced by the vertical arrow in cohomology

$$H^q(\mathfrak{g}, K_\infty; A_\mathfrak{q}(\lambda) \otimes \mathcal{M}_\lambda) \longrightarrow H^q(\mathfrak{g}, K_\infty; {}^{\mathrm{a}}\mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} \mathbb{D}_{\mu'} \otimes \mathcal{M}_\lambda)$$

is a bijection in the lowest degree of nonzero cohomology; this lowest degree is

$$q = v\left[\frac{u^2}{4}\right] + \frac{n(u-1)(v-1)}{4}.$$

Proof. We have an inclusion between the two complexes

$$\mathrm{Hom}_{K^0_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), A_\mathfrak{q}(\lambda) \otimes \mathcal{M}_\lambda)) \to \mathrm{Hom}_{K^0_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} \mathbb{D}_{\mu'} \otimes \mathcal{M}_\lambda).$$

In the complex on the left all differentials are zero. It follows from the work of Kostant that we have a splitting

$$\mathrm{Hom}(\Lambda^\bullet(\mathfrak{u}_P), \mathcal{M}_\lambda)) = \mathbb{H}^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda) \oplus AC^\bullet$$

where $\mathbb{H}^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda)$ is the space of harmonic forms (and this space is isomorphic to the cohomology $H^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda)$.) and where $AC^\bullet$ is an acyclic complex.

We have Delorme's formula

$$\mathrm{Hom}_{K^0_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})} \mathbb{D}_{\mu'} \otimes \mathcal{M}_\lambda) = \mathrm{Hom}_{K^M_\infty}(\Lambda^\bullet(\mathfrak{m}/\mathfrak{k}^M), \mathbb{D}_{\mu'} \otimes \mathrm{Hom}(\Lambda^\bullet(\mathfrak{u}_P), \mathcal{M}_\lambda)) =$$

$$\mathrm{Hom}_{K^M_\infty}(\Lambda^\bullet(\mathfrak{m}/\mathfrak{k}^M), \mathbb{D}_{\mu'} \otimes \mathbb{H}^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda)) \oplus \mathrm{Hom}_{K^M_\infty}(\Lambda^\bullet(\mathfrak{m}/\mathfrak{k}^M), \mathbb{D}_{\mu'} \otimes AC^\bullet) \tag{9.146}$$

The $(\mathfrak{m}/K^M_\infty)$ has a lowest $K^M_\infty)$ type $\vartheta(\mu')$, which can be computed easily from 3.1.4 and we have

$$\mathrm{Hom}_{K^M_\infty}(\Lambda^\bullet(\mathfrak{m}/\mathfrak{k}^M), \mathbb{D}_{\mu'} \otimes \mathbb{H}^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda)) = \mathrm{Hom}_{K^M_\infty}(\Lambda^\bullet(\mathfrak{m}/\mathfrak{k}^M), \mathbb{D}_{\mu'}(\vartheta(\mu')) \otimes \mathbb{H}^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda)).$$

Using the formula in [Vo-Zu] for the highest weight of the lowest K_∞-type $\Theta(\mathfrak{q}, \lambda)$ in $A_\mathfrak{q}(\lambda)$ we see that $\Theta(\mathfrak{q}, \lambda)$ is the lowest K_∞ type in $\mathrm{Ind}_{K^M_\infty}^{K_\infty}$. This implies that the map

$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathbb{A}_\mathfrak{q}(\lambda)(\Theta(\mathfrak{q}, \lambda) \otimes \mathcal{M}_\lambda) \to \mathrm{Hom}_{K^M_\infty}(\Lambda^\bullet(\mathfrak{m}/\mathfrak{k}^M), \mathbb{D}_{\mu'} \otimes \mathbb{H}^\bullet(\mathfrak{u}_P, \mathcal{M}_\lambda)) \tag{9.147}$$

is an isomorphism of vector spaces (but not of complexes). But since the complex on the right is zero in degrees $\bullet < q$ it follows that the classes in the image of $\mathrm{Hom}_{K_\infty}(\Lambda^q(\mathfrak{g}/\mathfrak{k}), A_\mathfrak{q}(\lambda)(\Theta(\mathfrak{q}, \lambda)) \otimes \mathcal{M}_\lambda)$ survive in cohomology.

□

We got to the global context, we have a diagram

$$\begin{array}{ccc} J_{\sigma_\infty} \otimes J_{\sigma_f}^{K_f} & \hookrightarrow & L^2_{\mathrm{disc}}(G(\mathbb{Q})\backslash G(\mathbb{A})/K_f, \omega^{-1}_{\mathcal{M}_\lambda}|_{S(\mathbb{R})^0}) \\ \downarrow & & \downarrow \mathcal{F}^P \\ {}^{\mathrm{a}}\mathrm{Ind}_{P(\mathbb{A})}^{G(\mathbb{A})} \mathbb{D}_{\mu'} \otimes V_{\sigma_f}^{K_f} & \hookrightarrow & \mathcal{A}(P(\mathbb{Q})U(\mathbb{A})\backslash G(\mathbb{A})/K_f) \end{array} \tag{9.148}$$

This induces maps in cohomology

$$\begin{array}{ccc} H^\bullet(\mathfrak{g},K_\infty,J_{\sigma_\infty}\otimes\mathcal{M}_\lambda)\otimes J_{\sigma_f}^{K_f} & \to & H^\bullet(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_\lambda) \\ \downarrow & & \downarrow \mathcal{F}^P \\ H^\bullet(\mathfrak{g},K_\infty,{}^{\mathrm{a}}\mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})}\mathbb{D}_{\mu'}\otimes\mathcal{M}_\lambda)\otimes V_{\sigma_f}^{K_f} & \hookrightarrow & H^\bullet(\partial_P\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_\lambda) \end{array} \tag{9.149}$$

The left vertical arrow is non zero for $\bullet = q$, the horizontal arrow in the bottom line is injective for all values of $\bullet$ (Borel see) hence the horizontal arrow in the top line is non zero in degree $\bullet = q$.

Of course we also should investigate the horizontal arrow in the to line in all degrees, this question becomes delicate. To answer it we should invoke the results in Franke's paper [ ] or we could work with proposition (8.1.4) or its corollary (8.1.1).

In the extremal case $u = n, v = 1$ the parabolic subgroup P is all of G and $A_\mathfrak{q}(\lambda) = \mathbb{D}_\lambda$. In this case, and only this case, the representation $A_\mathfrak{q}(\lambda)$ is tempered.

In the other extremal case that $u = 1, v = n$ the representation J_{σ_∞} is one dimensional - (basically it is the space of constant functions twisted by a character on the group of connected components) - in this case the map in the top row is understood in terms of the topological model (Franke + Diploma students).

9.6.5 Congruences

We formulate a condition (*NUQuot*) (No unitarizable quotient) for the induced module:

The induced module $I_P^G(\sigma_f)$ as module under the Hecke- algebra does not have a non trivial quotient which admits a unitary scalar product (here it may be necessary to pass to the corresponding representation of $G(\mathbb{A}_f)$).

The negation of this condition (*UQuot*) says that for all primes p the induced module $I_P^G\sigma_p$ has a unitarizable quotient.

This condition has been discussed in [Ha-Eis] Kap. II, 2.3.

If we have (*NUQuot*) then

$$\mathrm{Hom}_{\mathcal{H}^G_{K_f}}(I_P^G(\sigma_f), H^\bullet_!(\mathcal{S}^G_{K_f},\mathcal{M}\otimes\mathbb{C})) = 0 \tag{9.150}$$

this implies that the Manin-Drinfeld is valid and this implies that our above section is defined over F, i.e. we get a unique section of Hecke-modules

$$\mathrm{Eis}: H^{q-l(w)})(\mathcal{S}^M_{K_f^M},\mathcal{M}(w\cdot\lambda)\otimes F)(\sigma_f) \to H^q(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_\lambda\otimes F). \tag{9.151}$$

Then is looks as if the second term is completely uninteresting, but in fact it is not. In the lecture notes volume [Ha-Eis] we raise the question whether it influences the structure of the integral cohomology $H^q_{\mathrm{int}}(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_\lambda\otimes F)$. In some cases we have convincing experimental evidence that "arithmetic" of the ratio of special values

$$\frac{1}{\Omega(\sigma_f)} \prod_a \frac{\Lambda^{\mathrm{coh}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, <\eta_a, \tilde{\mu}^{(1)}> -ab(w,\lambda))}{\Lambda^{\mathrm{coh}}(\sigma_f, r_a^{\mathfrak{u}_P^\vee}, <\eta_a, \tilde{\mu}^{(1)}> -ab(w,\lambda)+1)} \tag{9.152}$$

has influence on the structure integral of the cohomology. Under certain conditions the above expression is a product of an algebraic part and the value of a motivic extension class. Primes dividing the denominator of the algebraic part may occur in the denominator of the Eisenstein class and we will have congruences (See (8.2.2),(8.35). This will be explained in the next section in the special case of the group $\mathrm{GSp}_2/\mathbb{Z}$.

Attaching motives to σ_f???

The condition (*NUQuot*)) will be true if λ is sufficiently regular but for non regular weights it fails. If the weight is not regular then we may have a pole of the Eisenstein series at $z = 0$. This possibility has to be discussed, it can only happen if we have *(UQuot)*. But even if we have *(UQuot)* we may not have a pole.

Let us assume that we have *(UQuot)* and the Eisenstein operator is holomorphic at $z = 0$. Then we may have several copies of $J(\sigma_f)$ in $H_!^\bullet(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_\lambda \otimes \mathbb{C})$. This defines again an isotypical submodule $H_!^\bullet(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_\lambda \otimes F)(\bar{\sigma_f})$. We get an exact sequence

$$0 \to H_!^\bullet(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_\lambda \otimes F)(\bar{\sigma_f}) \to \mathcal{X}(\sigma_f) \to J(\sigma_f) \to 0 \tag{9.153}$$

This is a sequence of Hecke-modules over F, the section (9.42) provides a section over $\mathbb{C}$.

If our locally symmetric space $\mathcal{S}_{K_f}^G$ the set of complex points of a Shimura variety then we can interpret this sequence as a mixed motive. This motive has an extension class in the category of mixed Hodge-structures

$$[\mathcal{X}(\sigma_f)]_{B-dRh} \in \mathrm{Ext}^1_{B-dRh}(J(\sigma_f), H_!^\bullet(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_\lambda \otimes F)(\bar{\sigma_f})) \tag{9.154}$$

and in some cases we can compute this class (we have to look at a suitable bi-extension) and express it in terms of the second term in the constant term (See [MixMot-2013.pdf].)

We have seen that in many situations the space $\mathcal{S}^M_{K_f^M}$ is not the set of complex points of a Shimura variety and therefore we do not know how to attach a motive or an ℓ adic Galois representation to it. (Sometimes we know how to attach a motive to it but it is simply a Tate motive). But if it happens that the module $J(\sigma_f)$ produces a non trivial submodule $H_!^\bullet(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_\lambda \otimes F)(\bar{\sigma_f}))$ then the situation changes and we can attach a Galois-module $H_!^\bullet(\mathcal{S}_{K_f}^G, \tilde{\mathcal{M}}_\lambda \otimes F_\lambda)(\bar{\sigma_f}))$ to it which contains a lot of information about σ_f. Again we refer to ([MixMot-2013.pdf].) We have seen in [Ha-Eis] (3.1.4.) that this can happen.

The motivic interpretation of Shahidis theorem

We go back to a general submodule $\sigma_f = \sigma_f^{(1)} \times \sigma_f^{(2)} = \sigma_f \in \mathrm{Coh}(H^\bullet_{\mathrm{cusp}}(\mathcal{S}^M_{K_f^M}, \tilde{\mathcal{M}}_{w\cdot\lambda})$, we drop the assumptions above. We assume that we can attach motives $\mathbb{M}(\sigma_f^{(1)}, r_1), \mathbb{M}(\sigma_f^{(2)}, r_1)$ where r_1 is the tautological representation. (Actually we do not need the motives it suffices to have the compatible systems of $\mathfrak{l}$-adic representations) Then we can attach the Rankin-Selberg motive to this pair

$$\mathbb{M}_{\mathrm{RS}}(\sigma_f, \mathrm{Ad}) = \mathbb{M}(\sigma_f^{(1)}, r_1) \times \mathbb{M}(\sigma_f^{(2)}, r_1)^\vee = \mathrm{Hom}(\mathbb{M}(\sigma_f^{(2)}, r_1), \mathbb{M}(\sigma_f^{(1)}, r_1)) \otimes \mathbb{Z}(-\mathbf{w}(\mu^{(2)}, r_2)) \tag{9.155}$$

Under the assumption of the theorem the we have $\mathbb{M}(\sigma_f^{(1)}, r_1) \xrightarrow{\sim} \mathbb{M}(\sigma_f^{(2)}, r_1)$ and we see that the Galois module $\mathrm{Hom}(\mathbb{M}(\sigma_f^{(2)}, r_1), \mathbb{M}(\sigma_f^{(1)}, r_1))$ contains a copy of $\mathbb{Z}_\mathfrak{l}(0)$ and therefore we get an exact sequence of Galois modules

$$0 \to \mathbb{Z}(-\mathbf{w}(\mu^{(2)}, r_2)) \to \mathbb{M}_{\mathrm{RS}}(\sigma_f, \mathrm{Ad})_{\text{ét},\mathrm{Ad}} \to \mathbb{M}^{(0)}_{\mathrm{RS}}(\sigma_f, \mathrm{Ad})_{\text{ét},\mathrm{Ad}} \to 0$$

Hence the motivic L function is a product

$$L(\mathbb{M}_{\mathrm{RS}}(\sigma_f, \mathrm{Ad})_{\text{ét},\mathrm{Ad}}, s) = L(\mathbb{Z}(-\mathbf{w}(\mu^{(2)}), s) L(\mathbb{M}^{(0)}_{\mathrm{RS}}(\sigma_f, \mathrm{Ad})_{\text{ét},\mathrm{Ad}}, s)$$

If we substitute for s the expression

$$\frac{\mathbf{w}(r_1, \mu_1^{(1)}) + \mathbf{w}(r_2, \mu_2^{(1)})}{2} - b(w, \lambda) + s = \mathbf{w}(r_2, \mu_2^{(1)}) - b(w, \lambda) + s$$

then we find

$$L(\mathbb{M}_{\mathrm{RS}}(\sigma_f, \mathrm{Ad})_{\text{ét},\mathrm{Ad}}, s) = \zeta(-b(w, \lambda) + s) L(\mathbb{M}^{(0)}_{\mathrm{RS}}(\sigma_f, \mathrm{Ad})_{\text{ét},\mathrm{Ad}}, s)$$

Then the motivic interpretation of Shahidis theorem is, that $L(\mathbb{M}^{(0)}_{\mathrm{RS}}(\sigma_f, \mathrm{Ad})_{\text{ét},\mathrm{Ad}}, \mathbf{w}(r_2, \mu_2^{(1)}) - b(w, \lambda) + s)$ is holomorphic at $s = 0$ and non zero (this is in a sense the prime number theorem for this L function) and therefore - if we have $b(w, \lambda) = -1$- the pole comes from the first order pole of the Riemann -ζ function. If now $\sigma_f^{(1)} \times \sigma_f^{(2)} = \sigma_f$ occurs in the cuspidal cohomology then we have an inclusion

$$\mathbb{D}_\mu \times H_{\sigma_f} \hookrightarrow \mathcal{A}(M(\mathbb{Q}) \backslash M(\mathbb{A}) / K_f^M)$$

We form the Eisenstein intertwining operator and compose it with constant Fourier coefficient, then we get

$$\mathcal{F}^P \circ \mathrm{Eis}(s) : f \mapsto f + C(\sigma, s) T^{\mathrm{loc}}(s)(f) \tag{9.156}$$

The operator $T^{\mathrm{loc}}(s) = T^{\mathrm{loc}}_\infty(s) \otimes \bigotimes T^{\mathrm{loc}}_p(s)$ is holomorphic at $s = 0$. Under our assumptions the function $C(\sigma, s)$ has a first order pole at $s = 0$ and we get a residual intertwining operator

$$\mathrm{Res}_{s=0} : \mathrm{Ind}_P^G \mathbb{D}_\mu \times H_{\sigma_f} \otimes (0) \to \mathcal{A}^{(2)}(G(\mathbb{Q}) \backslash G(\mathbb{A}) / K_f) \tag{9.157}$$

Rationality results

Finally we want to discuss the case that $P\neq\Theta(P)=Q$. If this happens then $\mathcal{S}^G_{K_f}$ is never a Shimura variety. We have isotypical pieces (see (9.22))

$$H_!^{\bullet-l(w)}(\mathcal{S}^M_{K_f^M},\tilde{\mathcal{M}}(w\cdot\lambda)\otimes F)(\sigma_f)\oplus H_!^{\bullet-l(w')}(\mathcal{S}^{M'}_{K_f^{M'}},\tilde{\mathcal{M}}(w'\cdot\lambda)\otimes F)(\sigma'_f) \tag{9.158}$$

and we know that component of the Eisenstein cohomology consists of the classes

$$\{\psi_f\oplus\mathcal{L}(\sigma_f)T_f^{\mathrm{loc}}(\psi_f)\} \tag{9.159}$$

where $\mathcal{L}(\sigma_f)$ is an element of F and for all $\iota:F\to\mathbb{C}$ we have

$$\iota(\mathcal{L}(\sigma_f))=\frac{1}{\Omega(\iota\circ\sigma_f)}C(\sigma_\infty,\lambda)C(\iota\circ\sigma_f,\lambda) \tag{9.160}$$

If the factor at infinity $C(\sigma_\infty,\lambda)\neq 0$ then we get from this rationality results for the ratios of L-values. (See [Ha-Mum], [Ha-Rag]) These rationality results will be important when we discuss the arithmetic nature of the numbers in**??**

Combining the results of Borel–Garland [3] and Mœglin–Waldspurger [35] we get that the homomorphism

$$\bigoplus_{u|n}\bigoplus_{\sigma_f:\mathrm{segment}}H^\bullet(\mathfrak{g},K_\infty;A_{\mathfrak{q}}(\lambda)\otimes\mathcal{M}_\lambda)\otimes J_{\sigma_f}\to H^\bullet_{(2)}(\mathcal{S}^G_{K_f},\mathcal{M}_\lambda) \tag{9.161}$$

is surjective. This gives us the decomposition into isotypical spaces of $H^\bullet_{(2)}(\mathcal{S}^G_{K_f},\mathcal{M}_\lambda)$. We separate the cuspidal part ($v=1$) from the residual part and get

$$H^\bullet_{(2)}(\mathcal{S}^G_{K_f},\mathcal{M}_\lambda)=\bigoplus_{\pi_f:\mathrm{cuspidal}}H^\bullet_{\mathrm{cusp}}(\mathcal{S}^G_{K_f},\mathcal{M}_\lambda)(\pi_f)\;\oplus\bigoplus_{\substack{u|n\\u<n}}\bigoplus_{\sigma_f:\mathrm{segment}}\overline{H^\bullet(\mathfrak{g},K_\infty;A_{\mathfrak{q}}(\lambda)\otimes\mathcal{M}_\lambda)}\otimes J_{\sigma_f},$$

where the bar on top means we have gone to its image via the map in (9.161). It follows from the theorem of Jacquet–Shalika [29] that there are no intertwining operators between the summands.

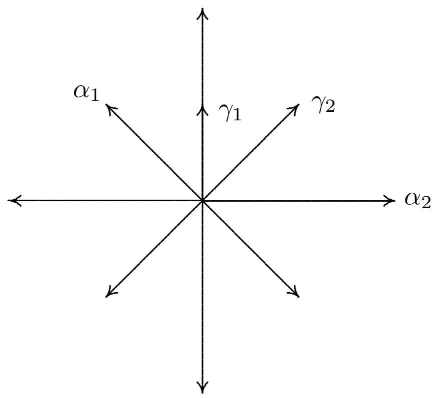
In the extremal case $u=n,v=1$ the parabolic subgroup P is all of G and $A_{\mathfrak{q}}(\lambda)=\mathbb{D}_\lambda$. In this case and only this case the representation $A_{\mathfrak{q}}(\lambda)$ is tempered, and the lowest degree of nonvanishing cohomology is the number b_n^F. An easy computation shows that in the case $v>1$ the number $q<b_n^F$. Then our theorem above implies that in degree q

$$H^q(\gamma,K_\infty;A_{\mathfrak{q}}(\lambda)\otimes\mathcal{M}_\lambda)\otimes J_{\sigma_f}\to H^q(\mathcal{S}^G_{K_f},\mathcal{M}_\lambda)$$

is injective. This has also been proved by Grobner [10]. The above result, which we announced earlier (**??**), can be sharpened as in the following theorem. During the induction argument we use Thm. **??** for the reductive quotients M of the parabolic subgroups.

9.7 The example $G = \mathrm{Sp}_2/\mathbb{Z}$

9.7.1 Some notations and structural data



The maximal torus is

$$T_0/\mathbb{Z} = t = \{ \begin{pmatrix} t_1 & 0 & 0 & 0 \\ 0 & t_2 & 0 & 0 \\ 0 & 0 & t_2^{-1} & 0 \\ 0 & 0 & 0 & t_1^{-1} \end{pmatrix} \}$$

the simple roots are

$$\alpha_1(t) = t_1/t_2, \alpha_2(t) = t_2^2$$

and the fundamental dominant weights are

$$\gamma_1(t) = t_1, \gamma_2(t) = t_1 t_2$$

and finally we have

$$2\gamma_1^M = t_1/t_2$$

We choose a highest weight $\lambda = n_1\gamma_1 + n_2\gamma_2$ let $\mathcal{M}_\lambda$ be a resulting module for $G/\operatorname{Spec}(\mathbb{Z})$. We get the following list of Kostant representatives for the Siegel parabolic subgroup P and they provide the following list of weights.

$$\begin{aligned} 1 \cdot \lambda &= \lambda = \tfrac{1}{2}(2n_2 + n_1)\gamma_2 + n_1\gamma_1^{M_1} \\ s_2 \cdot \lambda &= \tfrac{1}{2}(-2 + n_1)\gamma_2 + (2n_2 + n_1 + 2)\gamma_1^{M_1} \\ s_2 s_1 \cdot \lambda &= \tfrac{1}{2}(-4 - n_1)\gamma_2 + (2 + 2n_2 + n_1)\gamma_1^{M_1} \\ s_2 s_1 s_2 \cdot \lambda &= \tfrac{1}{2}(-6 - 2n_2 - n_1)\gamma_2 + n_1\gamma_1^{M_1}, \end{aligned}$$

We choose for $K_\infty \subset \mathrm{Sp}_2(\mathbb{R})$ the standard maximal compact subgroup $U(2)$, it is the centralizer of the matrix

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

which defines a complex structure. With this choice we can define $\mathcal{S}^G_{K_f} = G(\mathbb{Q})\backslash G(\mathbb{R})/K_\infty \times G(\mathbb{A}_f)/K_f$.

9.7.2 The cuspidal cohomology of the Siegel-stratum

We consider the cohomology groups $H^\bullet(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda)$ and the resulting fundamental exact sequence. We have the boundary stratum $\partial_P(\mathcal{S}^G_{K_f})$ with respect to the Siegel parabolic. Let us assume that we are in the unramified case, then we get

$$H^\bullet(\partial_P(\mathcal{S}^G_{K_f}), \tilde{\mathcal{M}}_\lambda) = \bigoplus_{w\in W^P} H^{\bullet - l(w)}(\mathcal{S}^M_{K^M_f}, H^{l(w)}(\mathfrak{u}_P, \mathcal{M}_\lambda)) \tag{9.162}$$

We look at the case $w = s_2 s_1$ in this case we know how to describe the corresponding summand in terms of automorphic forms on Gl_2. We introduce the usual abbreviation $H^{l(w)}(\mathfrak{u}_P, \mathcal{M}_\lambda) = \mathcal{M}_\lambda(w\cdot\lambda)$.

Our coefficient modules are the modules attached to the highest weight

$$w\cdot\lambda = \mu = (2 + 2n_2 + n_1)\gamma_1^{M_1} + \frac{1}{2}(-4 - n_1)\gamma_2$$

Let us put $k = 4+2n_2+n_1$ and $m = \frac{1}{2}n_1$. We give the usual concrete realization for these modules as $\mathcal{M}_{2+2n_2+n_1}[n_2 - 3 - k] = \mathcal{M}_{k-2}[n_2 - 3 - k]$

Let us look at the space $\mathcal{S}^M_{K^M_f}$. The group $M/\ \mathrm{Spec}(\mathbb{Z})$ is isomorphic to Gl_2, it is the Levi-quotient of the Siegel parabolic. The group K^M_∞ is the image of $P(\mathbb{R}) \cap K_\infty$ under the projection $P(\mathbb{R}) \to M(\mathbb{R})$. This is the group $\mathbb{O}(2)$ it contains the standard choice $K^M_\infty(1) = \mathrm{SO}(2)$ as a subgroup of index 2. Hence we get a covering of degree 2

$$\mathcal{S}^{\tilde{M}}_{K^M_f} = M(\mathbb{Q})\backslash M(\mathbb{R})/K^M_\infty(1) \times M(\mathbb{A}_f)/K^M_f \to \mathcal{S}^M_{K^M_f} \tag{9.163}$$

We get an inclusion

$$i : H^1(\mathcal{S}^M_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)) \hookrightarrow H^1(\mathcal{S}^{\tilde{M}}_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)). \tag{9.164}$$

On the cohomology on the right we have the action of $\mathbb{O}(2)/\mathrm{SO}(2) = \mathbb{Z}/2\mathbb{Z}$ and the cohomology decomposes into a $+$ and a $-$ eigenspace. The inclusion i provides an isomorphism of the left hand side and the $+$ eigenspace.

This inclusion is of course compatible with the action of the Hecke algebra. If we pass to a suitable extension $F/\mathbb{Q}$ we get the decompositions into isotypic subspaces if we tensor our coefficient system by F. An isomorphism type σ_f occurs with multiplicity one on the left hand side and with multiplicity two on the right hand side. Over the ring O_F the modules $H^1_{\pm,\,\mathrm{int}}(\mathcal{S}^M_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)_F)(\sigma_f)$ are of rank one, hence we can find locally in the base $\mathrm{Spec}(\mathcal{O}_F)$ an isomorphism

$$T^{\mathrm{arith}}(\sigma_f) : H^1_+(\mathcal{S}^{\tilde{M}}_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f) \xrightarrow{\sim} H^1_-(\mathcal{S}^{\tilde{M}}_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f) \tag{9.165}$$

The isomorphism given by the fundamental class (see(7.24) interchanges the $+$ and the $-$ eigenspace, hence we can arrange our arithmetic intertwining operator such that it satisfies

$$T^{\mathrm{arith}}(\sigma_f \otimes |\delta_f|) = T^{\mathrm{arith}}(\sigma_f \otimes |\delta_f|)^{-1} \tag{9.166}$$

We consider the transcendental description of the cohomology groups

$$H^1(\mathcal{S}^{\tilde{M}}_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)_\mathbb{C}) = \bigoplus_{\sigma_f} H^1_+(\mathcal{S}^{\tilde{M}}_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)_\mathbb{C})(\sigma_f) \oplus H^1_-(\mathcal{S}^{\tilde{M}}_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)_\mathbb{C})(\sigma_f) \tag{9.167}$$

We consider the standard Borel subgroup $B\subset M$ the standard split torus $T_0\subset B$ it contains our torus Z_0. We define the character

$$\chi_\mu = (k, m+2) : B(\mathbb{R}) \to \mathbb{C}^\times,\ \chi(t) = \gamma_1^M(t)^k|\gamma_2|^{m+2}.$$

It yields the induced Harish-Chandra module $I_{B(\mathbb{R})}^{M(\mathbb{R})}\chi_\mu$: We consider the functions

$$f : M(\mathbb{R}) \to \mathbb{C}; f(bg) = \chi(b)f(g); f|T_1 \text{ is of finite type }.$$

This is in fact a $(\mathfrak{m}, K_\infty^{M,0})$ -module, it contains the discrete representation $\mathcal{D}_{\chi_\mu}$. We have the decomposition

$$\mathcal{D}_{\chi_\mu} = \bigoplus_{\nu\equiv 0(2), |\nu|\geq k} F\phi_{\chi,\nu}$$

where

$$\phi_{\chi,\nu}(g) = \phi_{\chi,\nu}(b\begin{pmatrix}\cos(\phi) & \sin(\phi)\\ -\sin(\phi) & \cos(\phi\end{pmatrix}) = \chi(b)e^{2\pi i\nu\phi}.$$

Of course $K_\infty^{M,0} = T_1(\mathbb{R}) = \{e(\phi) = \begin{pmatrix}\cos(\phi) & \sin(\phi)\\ -\sin(\phi) & \cos(\phi\end{pmatrix}\}$ and we can write $e(\phi)^\nu = e^{2\pi\nu i\phi}$.

We have the well known formula for the $((\mathfrak{m}, K_\infty^{M,0})$ cohomology

$$H^1((\mathfrak{m}, K_\infty^{M,0}), \mathcal{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda(w\cdot\lambda)) = \operatorname{Hom}_{K_\infty^{M,0}}(\Lambda^1(\mathfrak{m}/\mathfrak{k}^M), \mathcal{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda(w\cdot\lambda)) = \tag{9.168}$$

$$\mathbb{C}P_+^\vee\otimes\phi_{\chi,-k}\otimes v_{k-2} + \mathbb{C}P_-^\vee\otimes\phi_{\chi,k}\otimes v_{-k+2} = \mathbb{C}\omega_{k,m} + \mathbb{C}\bar{\omega}_{k,m} \tag{9.169}$$

Here $v_{k-2} = (X+iY)^{k-2}$, resp. $v_{2-k} = (X-iY)^{k-2}$ are two carefully chosen highest (resp. lowest) weight vectors with respect to the action of $K_\infty^{M,0}$. The elements $P_\pm$ are the usual elements in $\mathfrak{m}/\mathfrak{k}$. We choose a model space H_{σ_f} for σ_f i.e. a free rank one $\mathcal{O}_F$ -module on which the Hecke algebra acts by the homomorphism $\sigma_f : \mathcal{H}^M_{K^M_f} \to \mathcal{O}_F$. We also choose and embedding $\iota : F \hookrightarrow \mathbb{C}$ and an $(\mathfrak{m}, K_\infty^{M,0})\times K_\infty^M\times\mathcal{H}^M_{K^M_f}$- invariant embedding

$$\Phi_\iota : \mathcal{D}_{\chi_\mu}\otimes H_{\sigma_f}\otimes_{F,\iota}\mathbb{C} \to L^2_0(M(\mathbb{Q})\backslash M(\mathbb{A})) \tag{9.170}$$

this is unique up to a scalar in $\mathbb{C}^\times$ because the representation is irreducible and occurs with multiplicity one in the right hand side. This yields an isomorphism

$$\Phi^1_\iota : H^1((\mathfrak{m}, K_\infty^{M,0}), \mathcal{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda(w\cdot\lambda))\otimes H_{\sigma_f}\otimes_{F,\iota}\mathbb{C} \xrightarrow{\sim} H^1(\mathcal{S}^{\tilde{M}}_{K^M_f}, \mathcal{M}_\lambda(w\cdot\lambda)_\mathbb{C})(\iota\circ\sigma_f)$$

We observe that the element $\epsilon = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \in K_\infty^M$ has the following effect

$$\mathrm{Ad}(\epsilon)(P_+) = P_- \ , \epsilon(\phi_{\chi,k}) = \phi_{\chi,-k} \ \text{ and } \epsilon(v_{k-2}) = (-1)^m v_{2-k} \tag{9.171}$$

Hence we see that

$$\omega^{(+)}_{k,m} = \omega_{k,m} + (-1)^m \bar{\omega}_{k,m} \text{ resp. } \omega^{(-)}_{k,m} = \omega_{k,m} - (-1)^m \bar{\omega}_{k,m} \tag{9.172}$$

are generators of the $+$ and the $-$ eigenspace in $H^1(\mathfrak{m}, K_\infty^{M,0}, \mathcal{D}_{\chi_\mu} \otimes \mathcal{M}_\lambda(w\cdot\lambda))$. Therefore our map Φ and the choice of these generators provide isomorphisms

$$\Phi_\iota^{(+)} : H_{\sigma_f} \otimes_{F,\iota} \mathbb{C} \xrightarrow{\sim} H^1_+(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_{\mathbb{C}})(\iota\circ\sigma_f), \tag{9.173}$$

$$\Phi_\iota^{(-)} : H_{\sigma_f} \otimes_{F,\iota} \mathbb{C} \xrightarrow{\sim} H^1_-(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_{\mathbb{C}})(\iota\circ\sigma_f) \tag{9.174}$$

The choice of P_+, P_- and $\phi_{\chi,-\nu}$ is canonic, hence we see that the identifications depend only on Φ_ι , which is unique up to a scalar. This means that the composition

$$T^{\mathrm{trans}}(\iota\circ\sigma_f) = \Phi_\iota^{(-)} \circ (\Phi_\iota^{(+)})^{-1}$$

$$: H^1_+(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_{\mathbb{C}})(\iota\circ\sigma_f) \xrightarrow{\sim} H^1_- \mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_{\mathbb{C}})(\iota\circ\sigma_f)$$

yields a second (canonical) identification between the $\pm$ eigenspaces in the cohomology. Our arithmetic intertwining operator (See (9.165) yields an array of intertwining operators

$$T^{\mathrm{arith}}(\sigma_f)\otimes_{F,\iota}\mathbb{C} : H^1_+(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f)\otimes_{F,\iota}\mathbb{C} \xrightarrow{\sim} H^1_-(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f)\otimes_{F,\iota}\mathbb{C} \tag{9.175}$$

Hence get an array of periods which compare these two arrays of intertwining operators

$$\Omega(\sigma_f,\iota) T^{\mathrm{trans}}(\iota\circ\sigma_f) = T^{\mathrm{arith}}(\sigma_f)\otimes_{F,\iota}\mathbb{C} \tag{9.176}$$

Our formula (9.166) tells us that we can arrange the intertwining operators such that

$$\Omega(\sigma_f \otimes |\delta_f|, \iota) = \Omega(\sigma_f,\iota)^{-1} \tag{9.177}$$

These periods are uniquely defined up to a unit in $\mathcal{O}_F^\times$.

The Eisenstein intertwining

We pick a σ_f which occurs in $H^1_!(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))$, we choose a $\iota : F \hookrightarrow \mathbb{C}$ and we choose an embedding

$$\Phi_\iota : \mathcal{D}_{\chi_\mu} \otimes H_{\sigma_f} \otimes_{F,\iota} \mathbb{C} \hookrightarrow L^2_{\mathrm{cusp}}(M(\mathbb{Q})\backslash M(\mathbb{A})) \tag{9.178}$$

and from this we get the Eisenstein intertwining

$$\mathrm{Eis}\circ\Phi_\iota : \ \mathrm{Ind}_{P(\mathbb{R})}^{G(\mathbb{R})}(\mathcal{D}_{\chi_\mu}) \otimes H_{\sigma_f} \otimes_{F,\iota} \mathbb{C} \to \mathcal{A}(G(\mathbb{Q})\backslash G(\mathbb{A})) \tag{9.179}$$

(Here we use that $K_f = \mathrm{GSp}_2(\hat{\mathbb{Z}})$.) Hence we get an intertwining operator

$$\mathrm{Eis}^\bullet: \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), I_P^G(\mathcal{D}_{\chi_\mu})\otimes\mathcal{M}_\lambda)\otimes H_{\sigma_f}\otimes_{F,\iota}\mathbb{C}\to \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), \mathcal{A}(G(\mathbb{Q})\backslash G(\mathbb{A}))\otimes\mathcal{M}_\lambda) \tag{9.180}$$

and this induces a homomorphism in cohomology

$$H^3(\mathfrak{g},K_\infty, I_P^G(\mathcal{D}_{\chi_\mu})\otimes\mathcal{M}_\lambda)\otimes H_{\sigma_f}\otimes_{F,\iota}\mathbb{C})\to H^3(\mathcal{S}^G_{K_f},\tilde{\mathcal{M}}_{\lambda,\mathbb{C}}) \tag{9.181}$$

and we want to compose it with the restriction to the cohomology of the boundary. We have to compose it with the the constant Fourier coefficient $\mathcal{F}^P:\mathcal{A}(G(\mathbb{Q})\backslash G(\mathbb{A}))\to\mathcal{A}(P(\mathbb{Q})U(\mathbb{A})\backslash G(\mathbb{A}))$. We know that $\mathcal{F}^P$ maps into the subspace

$$I_P^G\mathcal{D}_{\chi_\mu}\otimes H_{\sigma_f}\otimes_{F,\iota}\mathbb{C}\xrightarrow{\mathcal{F}^P} I_P^G\mathcal{D}_{\chi_\mu}\otimes H_{\sigma_f}\otimes_{F,\iota}\mathbb{C}\bigoplus I_P^G\mathcal{D}_{\chi_{\mu'}}\otimes H_{\sigma_f^{w_P}|\gamma_{P,f}|^{2f_P}}\otimes_{F,\iota}\mathbb{C} \tag{9.182}$$

where $\mu' = w_P w\cdot\lambda = s_2\cdot\lambda = (2+2n_2+n_1)\gamma_1^{M_1}+\frac{1}{2}(-2+n_1)\gamma_2$. More precisely we know that for $h\in I_P^G\mathcal{D}_{\chi_\mu}\otimes H_{\sigma_f}\otimes_{F,\iota}\mathbb{C}$

$$\mathcal{F}^P(h) = h + C(\sigma,0)T^{\mathrm{loc}}(0)(h) \tag{9.183}$$

where $T^{\mathrm{loc}}(0) = T_\infty^{\mathrm{loc}}\otimes\otimes_p T_p^{\mathrm{loc}}$. The local intertwining operator at the finite primes is normalized, it maps the standard spherical function into the standard spherical function. The operator T_∞^{loc} will be discussed below.

Our general formula for the constant term yields for an $h = h_\infty\times h_f$

Explain in more detail

$$\mathcal{F}^P(h) = h + C(\sigma_\infty,\lambda)T_\infty^{\mathrm{loc}}(h_\infty)\frac{L^{\mathrm{coh}}(f,n_1+n_2+2)}{L^{\mathrm{coh}}(f,n_1+n_2+3)}\frac{\zeta(n_1+1)}{\zeta(n_1+2)}\times T_f^{\mathrm{loc}}(0)(h_f) \tag{9.184}$$

(For the following compare SecOps.pdf) We analyze the factor $C(\sigma_\infty,\lambda)T_\infty^{\mathrm{loc}}$ more precisely we study the effect of this operator on the cohomology. Let us look at the map between complexes

$$T_\infty^{\mathrm{loc},\bullet}: \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), I_P^G\mathcal{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda)\to \ \mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}), I_P^G\mathcal{D}_{\chi_{\mu'}}\otimes\mathcal{M}_\lambda) \tag{9.185}$$

The intertwining operator $T_\infty^{\mathrm{loc}}: I_P^G\mathcal{D}_{\chi_\mu}\to I_P^G\mathcal{D}_{\chi_{\mu'}}$ has a kernel $\mathbb{D}_{\chi_\mu}$, this is a discrete series representation. We know that

$$\mathrm{Hom}_{K_\infty}(\Lambda^\bullet(\mathfrak{g}/\mathfrak{k}),\mathbb{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda) = \ \mathrm{Hom}_{K_\infty}(\Lambda^3(\mathfrak{g}/\mathfrak{k}),\mathbb{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda) = \tag{9.186}$$

$$H^3(\mathfrak{g},K_\infty,\mathbb{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda) = \mathbb{C}\Omega_{2,1}\oplus\mathbb{C}\Omega_{1,2} \tag{9.187}$$

We have the surjective homomorphism

$$H^3(\mathfrak{g},K_\infty,\mathbb{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda)\to H^3(\Lambda^3(\mathfrak{g}/\mathfrak{k}), I_P^G\mathcal{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda) = H^1(\mathfrak{m},K_\infty^M,\mathcal{D}_{\chi_\mu}\otimes H^2(\mathfrak{u}_P,\mathcal{M}_\lambda) = \mathbb{C}\omega^{(3)} \tag{9.188}$$

the differential form $\Omega_{2,1}+\epsilon(\lambda)\Omega_{1,2}$ maps to a non zero multiple $A(\lambda)\omega^{(3)}$. (The factor $\epsilon(\lambda)$ is a sign depending on λ). We can write $\Omega_{2,1}-\epsilon(\lambda)\Omega_{1,2}=d\psi$ where

$$\psi \in \ \mathrm{Hom}_{K_\infty}(\Lambda^2(\mathfrak{g}/\mathfrak{k}), \mathbb{D}_{\chi_\mu}\otimes \mathcal{M}_\lambda) \tag{9.189}$$

and $\omega = T_\infty^{\mathrm{loc},2}(\psi) \in \ \mathrm{Hom}_{K_\infty}(\Lambda^2(\mathfrak{g}/\mathfrak{k}), \mathcal{D}_{\chi_{\mu'}}\otimes \mathcal{M}_\lambda)$ is a closed form, hence it provides a cohomology class. Let us denote this cohomology class by $\kappa(\omega^{(3)})$.

Choosing $\omega^{(3)}$ as a basis element and applying the Eisenstein intertwining operator (9.180) yields a homomorphism

$$\mathrm{Eis}^{(3)}\circ\Phi_\iota : H^1_!(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f\circ\iota) \to H^3(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_\lambda\otimes\mathbb{C}) \tag{9.190}$$

.

The local intertwining operator T_∞^{loc} maps $\omega^{(3)}$ to zero and hence it follows that the composition $r\circ\ \mathrm{Eis}^{(3)}$ is the identity, the Eisenstein intertwining operator yields a section on $H^1_!(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f)$. (Remember $w=s_2s_1$). If we define

$$H^3(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f) = r^{-1}(H^1_!(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f)) \tag{9.191}$$

(Induction does not play a role since the level is one) then we get the decomposition

$$H^3_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})\oplus H^3_{\mathrm{Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f) = H^3_!(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f) \tag{9.192}$$

The denominator of the Eisenstein class

We restrict this decomposition to the integral cohomology (better the image of the integral cohomology in the cohomology with rational coefficients)

$$H^3_{\mathrm{int}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f) \supset H^3_{!,\ \mathrm{int}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f)\oplus H^3_{\mathrm{int,\ Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f) \tag{9.193}$$

The image of $H^3_{\mathrm{int,\ Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f)$ under r is a submodule of finite index in $H^1_{!,\ \mathrm{int}}(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f))$ and the quotient is

$$\begin{aligned} H^3_{\mathrm{int}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f)/(H^3_{!,\ \mathrm{int}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f)\oplus H^3_{\mathrm{int,\ Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f)) = \\ H^1_{!\ \mathrm{int}}(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f))/\mathrm{image}(r). \end{aligned} \tag{9.194}$$

The quotient on the right hand side is $\mathcal{O}_F/\Delta(\sigma_f)$ where $\Delta(\sigma_f)$ is the denominator ideal. Tensoring the exact sequence

$$0\to H^3_{!,\ \mathrm{int}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f)\oplus H^3_{\mathrm{int,\ Eis}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f) \to H^1_{\mathrm{int}}(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f)) \to \mathcal{O}_F/\Delta(\sigma_f)\to 0 \tag{9.195}$$

by $\mathcal{O}_F/\Delta(\sigma_f)$ yields an inclusion

$$\mathrm{Tor}^1_{\mathcal{O}_F}(\mathcal{O}_F/\Delta(\sigma_f), \mathcal{O}_F/\Delta(\sigma_f) = \mathcal{O}_F/\Delta(\sigma_f)) \hookrightarrow H^3_{!,\ \mathrm{int}}(\mathcal{S}^G_{K_f}, \tilde{\mathcal{M}}_{\lambda F})(\sigma_f)\otimes \mathcal{O}_F/\Delta(\sigma_f) \tag{9.196}$$

and this explains the congruences.

The secondary class

We choose generators $\omega^{(3)}(\sigma_f)$(resp. $\omega^{(2)}(\sigma_f^{w_P}|\gamma_{P,f}|^{2f_P})$) for $H^1_{\mathrm{int}}(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\sigma_f)$(resp. $H^1_{\mathrm{int}}(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(s_2\cdot\lambda))(\sigma_f))$ (Perhaps we can do this only locally on $\mathrm{Spec}(\mathcal{O}_F)$.) We may arrange these generators such that $T^{\mathrm{arith}}(\sigma_f)(\omega^{(3)}(\sigma_f)) = \omega^{(2)}(\sigma_f^{w_P}|\gamma_{P,f}|^{2f_P})$. The isomorphism

$$\Phi_\iota^{(3)} : H^3(\mathfrak{g}, K_\infty, \mathcal{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda)\otimes H_{\sigma_f}\otimes_{F,\iota}\mathbb{C} \xrightarrow{\sim} H^1_{\mathrm{int}}(\mathcal{S}^{\tilde{M}}_{K_f^M}, \mathcal{M}_\lambda(w\cdot\lambda)_F))(\iota\circ\sigma_f) \tag{9.197}$$

maps

$$(\Omega_{2,1}+\epsilon(\lambda)\Omega_{1,2})\otimes\omega^{(3)}(\iota\circ\sigma_f)\mapsto\Omega_+(\sigma_f,\iota)\omega(\sigma_f)$$

where $\Omega_+(\sigma_f,\iota)$ is a period depending on the choice of Φ_ι. The element

$$(\Omega_{2,1}-\epsilon(\lambda)\Omega_{1,2})\otimes\omega^{(3)}(\iota\circ\sigma_f) = d\psi\otimes\omega^{(3)}(\iota\circ\sigma_f).$$

where $\psi\in\ \mathrm{Hom}_{K_\infty}(\Lambda^2(\mathfrak{g}/\mathfrak{k}), I_P^G\mathcal{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda)$. The operator $T^{\ \mathrm{loc}}(0)$ in (9.183) provides a homomorphism (9.185)

$$T^{\ \mathrm{loc},2}\otimes T_f^{\mathrm{loc}} :\ \mathrm{Hom}_{K_\infty}(\Lambda^2(\mathfrak{g}/\mathfrak{k}), I_P^G\mathcal{D}_{\chi_\mu}\otimes\mathcal{M}_\lambda)\otimes H_{\iota\circ\sigma_f}\to\ \mathrm{Hom}_{K_\infty}(\Lambda^2(\mathfrak{g}/\mathfrak{k}), I_P^G\mathcal{D}_{\chi_{\mu'}}\otimes\mathcal{M}_\lambda)\otimes H_{\iota\circ\sigma_f^{w_P}}|\gamma_P$$

Under this homomorphism the class ψ is mapped to a multiple of $\omega^{(2)}(\sigma_f^{w_P}|\gamma_{P,f}|^{2f_P})$). We can calculate this multiple, during this calculation we see a second period $\Omega_-(\sigma_f,\iota)$ depending on Φ_ι and the ratio of these periods will be our period $\Omega(\iota\circ\sigma_f)$ in formula (9.176) .

This period is independent of Φ_ι. To state the final result we denote by f the modular cusp form attached to σ_f, this is a modular form with coefficients in F, then $\iota\circ f$ is a modular form with coefficients in $\mathbb{C}$. By $\Lambda(f,s)$ we denote the usual completed L -function. We get

$$C(\sigma,0)T^{\ \mathrm{loc}}(\kappa(\omega^{(3)}(\iota\circ\sigma_f)) =$$

$$\Big(\frac{1}{\Omega(\sigma_f,\iota))^{\epsilon(k,m)}}\frac{\Lambda^{\mathrm{coh}}(\iota\circ f, n_1+n_2+2)}{\Lambda^{\mathrm{coh}}(\iota\circ f, n_1+n_2+3)}\frac{1}{\zeta(-1-n_1)}\Big)\frac{\zeta'(-n_1)}{\pi}\omega^{(2)}(\sigma_f^{w_P}|\gamma_{P,f}|^{2f_P}))$$

The factor inside the large brackets is essentially rational (it is in F and behaves invariantly under the action of the Galois group) the factor $\frac{\zeta'(-n_1)}{\pi}$ should viewed as a generator of a group of extension classes of mixed motives.

For me the most difficult part in the calculation is the treatment of the intertwining operator at ∞, this is carried out in SecOps.pdf. At the end of SecOps.pdf. I discuss the arithmetic applications and the conjectural relationship between the primes dividing the denominator of the expression in the large brackets and the denominators of the Eisenstein classes in (8.35)

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[MixMot-2015.pdf] Modular Construction of Mixed Motives

[SecOps.pdf] Secondary Operations on the Cohomology of Harish-Chandra Modules

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